

Implementing Multiple Precision Arithmetic

Holiday Draft Edition

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This text has been placed in the public domain. This text corresponds to the v0.28 release of the LibTomMath project.

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Prefaces to the Holiday Draft Edition

I started this text in April 2003 to complement my LibTomMath library. That is, explain how to implement the functions contained in LibTomMath. The goal is to have a textbook that any Computer Science student can use when implementing their own multiple precision arithmetic. The plan I wanted to follow was flesh out all the ideas and concepts I had floating around in my head and then work on it afterwards refining a little bit at a time. Chance would have it that I ended up with my summer off from Algonquin College and I was given four months solid to work on the text.

Choosing to not waste any time I dove right into the project even before my spring semester was finished. I wrote a bit off and on at first. The moment my exams were finished I jumped into long 12 to 16 hour days. The result after only a couple of months was a ten chapter, three hundred page draft that I quickly had distributed to anyone who wanted to read it. I had Jean-Luc Cooke print copies for me and I brought them to Crypto'03 in Santa Barbara. So far I have managed to grab a certain level of attention having people from around the world ask me for copies of the text was certain rewarding.

Now we are in December 2003. By this time I had pictured that I would have at least finished my second draft of the text. Currently I am far off from this goal. I've done partial re-writes of chapters one, two and three but they are not even finished yet. I haven't given up on the project, only had some setbacks. First O'Reilly declined to publish the text then Addison-Wesley and Greg is tried another which I don't know the name of. However, at this point I want to focus my energy onto finishing the book not securing a contract.

So why am I writing this text? It seems like a lot of work right? Most certainly it is a lot of work writing a textbook. Even the simplest introductory

material has to be lined with references and figures. A lot of the text has to be re-written from point form to prose form to ensure an easier read. Why am I doing all this work for free then? Simple. My philosophy is quite simply “Open Source. Open Academia. Open Minds” which means that to achieve a goal of open minds, that is, people willing to accept new ideas and explore the unknown you have to make available material they can access freely without hinderance.

I’ve been writing free software since I was about sixteen but only recently have I hit upon software that people have come to depend upon. I started LibTomCrypt in December 2001 and now several major companies use it as integral portions of their software. Several educational institutions use it as a matter of course and many freelance developers use it as part of their projects. To further my contributions I started the LibTomMath project in December 2002 aimed at providing multiple precision arithmetic routines that students could learn from. That is write routines that are not only easy to understand and follow but provide quite impressive performance considering they are all in standard portable ISO C.

The second leg of my philosophy is “Open Academia” which is where this textbook comes in. In the end, when all is said and done the text will be useable by educational institutions as a reference on multiple precision arithmetic.

At this time I feel I should share a little information about myself. The most common question I was asked at Crypto’03, perhaps just out of professional courtesy, was which school I either taught at or attended. The unfortunate truth is that I neither teach at or attend a school of academic reputation. I’m currently at Algonquin College which is what I’d like to call “somewhat academic but mostly vocational” college. In otherwords, job training.

I’m a 21 year old computer science student mostly self-taught in the areas I am aware of (which includes a half-dozen computer science fields, a few fields of mathematics and some English). I look forward to teaching someday but I am still far off from that goal.

Now it would be improper for me to not introduce the rest of the texts co-authors. While they are only contributing corrections and editorial feedback their support has been tremendously helpful in presenting the concepts laid out in the text so far. Greg has always been there for me. He has tracked my LibTom projects since their inception and even sent cheques to help pay tuition from time to time. His background has provided a wonderful source to bounce ideas off of and improve the quality of my writing. Mads is another fellow who has just “been there”. I don’t even recall what his interest in the LibTom projects is but I’m definitely glad he has been around. His ability to catch logical errors in my written English have saved me on several occasions to say the least.

What to expect next? Well this is still a rough draft. I've only had the chance to update a few chapters. However, I've been getting the feeling that people are starting to use my text and I owe them some updated material. My current tentative plan is to edit one chapter every two weeks starting January 4th. It seems insane but my lower course load at college should provide ample time. By Crypto'04 I plan to have a 2nd draft of the text polished and ready to hand out to as many people who will take it.

Finally, again, I'd like to thank my parents Vern and Katie St Denis for giving me a place to stay, food, clothes and word of encouragement whenever I seemed to need it. Thanks!

Tom St Denis

I found the opportunity to work with Tom appealing for several reasons, not only could I broaden my own horizons, but also contribute to educate others facing the problem of having to handle big number mathematical calculations.

This book is Tom's child and he has been caring and fostering the project ever since the beginning with a clear mind of how he wanted the project to turn out. I have helped by proofreading the text and we have had several discussions about the layout and language used.

I hold a masters degree in cryptography from the University of Southern Denmark and have always been interested in the practical aspects of cryptography.

Having worked in the security consultancy business for several years in São Paulo, Brazil, I have been in touch with a great deal of work in which multiple precision mathematics was needed. Understanding the possibilities for speeding up multiple precision calculations is often very important since we deal with outdated machine architecture where modular reductions, for example, become painfully slow.

This text is for people who stop and wonder when first examining algorithms such as RSA for the first time and asks themselves, "You tell me this is only secure for large numbers, fine; but how do you implement these numbers?"

Mads Rasmussen
São Paulo - SP
Brazil

It's all because I broke my leg. That just happened to be at about the same time that Tom asked for someone to review the section of the book about Karatsuba multiplication. I was laid up, alone and immobile, and thought "Why not?" I vaguely knew what Karatsuba multiplication was, but not really, so I thought I could help, learn, and stop myself from watching daytime cable TV, all at once.

At the time of writing this, I've still not met Tom or Mads in meatspace. I've been following Tom's progress since his first splash on the sci.crypt Usenet news group. I watched him go from a clueless newbie, to the cryptographic equivalent of a reformed smoker, to a real contributor to the field, over a period of about two years. I've been impressed with his obvious intelligence, and astounded by his productivity. Of course, he's young enough to be my own child, so he doesn't have my problems with staying awake.

When I reviewed that single section of the book, in its very earliest form, I was very pleasantly surprised. So I decided to collaborate more fully, and at least review all of it, and perhaps write some bits too. There's still a long way to go with it, and I have watched a number of close friends go through the mill of publication, so I think that the way to go is longer than Tom thinks it is. Nevertheless, it's a good effort, and I'm pleased to be involved with it.

Greg Rose, Sydney, Australia, June 2003.

Chapter 1

Introduction

1.1 Multiple Precision Arithmetic

1.1.1 What is Multiple Precision Arithmetic?

When we think of long-hand arithmetic such as addition or multiplication we rarely consider the fact that we instinctively raise or lower the precision of the numbers we are dealing with. For example, in decimal we almost immediately can reason that 7 times 6 is 42. However, 42 has two digits of precision as opposed to one digit we started with. Further multiplications of say 3 result in a larger precision result 126. In these few examples we have multiple precisions for the numbers we are working with. Despite the various levels of precision a single subset¹ of algorithms can be designed to accommodate them.

By way of comparison a fixed or single precision operation would lose precision on various operations. For example, in the decimal system with fixed precision $6 \cdot 7 = 2$.

Essentially at the heart of computer based multiple precision arithmetic are the same long-hand algorithms taught in schools to manually add, subtract, multiply and divide.

1.1.2 The Need for Multiple Precision Arithmetic

The most prevalent need for multiple precision arithmetic, often referred to as “bignum” math, is within the implementation of public-key cryptography

¹With the occasional optimization.

algorithms. Algorithms such as RSA [11] and Diffie-Hellman [12] require integers of significant magnitude to resist known cryptanalytic attacks. For example, at the time of this writing a typical RSA modulus would be at least greater than 10^{309} . However, modern programming languages such as ISO C [18] and Java [19] only provide intrinsic support for integers which are relatively small and single precision.

Data Type	Range
char	-128 ... 127
short	-32768 ... 32767
long	-2147483648 ... 2147483647
long long	-9223372036854775808 ... 9223372036854775807

Figure 1.1: Typical Data Types for the C Programming Language

The largest data type guaranteed to be provided by the ISO C programming language² can only represent values up to 10^{19} as shown in figure 1.1. On its own the C language is insufficient to accomodate the magnitude required for the problem at hand. An RSA modulus of magnitude 10^{19} could be trivially factored³ on the average desktop computer, rendering any protocol based on the algorithm insecure. Multiple precision algorithms solve this very problem by extending the range of representable integers while using single precision data types.

Most advancements in fast multiple precision arithmetic stem from the need for faster and more efficient cryptographic primitives. Faster modular reduction and exponentiation algorithms such as Barrett's algorithm, which have appeared in various cryptographic journals, can render algorithms such as RSA and Diffie-Hellman more efficient. In fact, several major companies such as RSA Security, Certicom and Entrust have built entire product lines on the implementation and deployment of efficient algorithms.

However, cryptography is not the only field of study that can benefit from fast multiple precision integer routines. Another auxiliary use of multiple precision integers is high precision floating point data types. The basic IEEE [13] standard floating point type is made up of an integer mantissa q , an exponent e and a sign bit s . Numbers are given in the form $n = q \cdot b^e \cdot -1^s$ where $b = 2$

²As per the ISO C standard. However, each compiler vendor is allowed to augment the precision as they see fit.

³A Pollard-Rho factoring would take only 2^{16} time.

is the most common base for IEEE. Since IEEE floating point is meant to be implemented in hardware the precision of the mantissa is often fairly small (23, 48 and 64 bits). The mantissa is merely an integer and a multiple precision integer could be used to create a mantissa of much larger precision than hardware alone can efficiently support. This approach could be useful where scientific applications must minimize the total output error over long calculations.

Another use for large integers is within arithmetic on polynomials of large characteristic (i.e. $GF(p)[x]$ for large p). In fact the library discussed within this text has already been used to form a polynomial basis library⁴.

1.1.3 Benefits of Multiple Precision Arithmetic

The benefit of multiple precision representations over single or fixed precision representations is that no precision is lost while representing the result of an operation which requires excess precision. For example, the product of two n -bit integers requires at least $2n$ bits of precision to be represented faithfully. A multiple precision algorithm would augment the precision of the destination to accommodate the result while a single precision system would truncate excess bits to maintain a fixed level of precision.

It is possible to implement algorithms which require large integers with fixed precision algorithms. For example, elliptic curve cryptography (*ECC*) is often implemented on smartcards by fixing the precision of the integers to the maximum size the system will ever need. Such an approach can lead to vastly simpler algorithms which can accommodate the integers required even if the host platform cannot natively accommodate them⁵. However, as efficient as such an approach may be, the resulting source code is not normally very flexible. It cannot, at runtime, accommodate inputs of higher magnitude than the designer anticipated.

Multiple precision algorithms have the most overhead of any style of arithmetic. For the the most part the overhead can be kept to a minimum with careful planning, but overall, it is not well suited for most memory starved platforms. However, multiple precision algorithms do offer the most flexibility in terms of the magnitude of the inputs. That is, the same algorithms based on multiple precision integers can accommodate any reasonable size input without the designer's explicit forethought. This leads to lower cost of ownership for the code as it only has to be written and tested once.

⁴See <http://poly.libtomcrypt.org> for more details.

⁵For example, the average smartcard processor has an 8 bit accumulator.

1.2 Purpose of This Text

The purpose of this text is to instruct the reader regarding how to implement efficient multiple precision algorithms. That is to not only explain a limited subset of the core theory behind the algorithms but also the various “house keeping” elements that are neglected by authors of other texts on the subject. Several well reknowned texts [1, 2] give considerably detailed explanations of the theoretical aspects of algorithms and often very little information regarding the practical implementation aspects.

In most cases how an algorithm is explained and how it is actually implemented are two very different concepts. For example, the Handbook of Applied Cryptography (*HAC*), algorithm 14.7 on page 594, gives a relatively simple algorithm for performing multiple precision integer addition. However, the description lacks any discussion concerning the fact that the two integer inputs may be of differing magnitudes. As a result the implementation is not as simple as the text would lead people to believe. Similarly the division routine (*algorithm 14.20, pp. 598*) does not discuss how to handle sign or handle the dividend’s decreasing magnitude in the main loop (*step #3*).

Both texts also do not discuss several key optimal algorithms required such as “Comba” and Karatsuba multipliers and fast modular inversion, which we consider practical oversights. These optimal algorithms are vital to achieve any form of useful performance in non-trivial applications.

To solve this problem the focus of this text is on the practical aspects of implementing a multiple precision integer package. As a case study the “LibTomMath”⁶ package is used to demonstrate algorithms with real implementations⁷ that have been field tested and work very well. The LibTomMath library is freely available on the Internet for all uses and this text discusses a very large portion of the inner workings of the library.

The algorithms that are presented will always include at least one “pseudo-code” description followed by the actual C source code that implements the algorithm. The pseudo-code can be used to implement the same algorithm in other programming languages as the reader sees fit.

This text shall also serve as a walkthrough of the creation of multiple precision algorithms from scratch. Showing the reader how the algorithms fit together as well as where to start on various taskings.

⁶Available at <http://math.libtomcrypt.org>

⁷In the ISO C programming language.

1.3 Discussion and Notation

1.3.1 Notation

A multiple precision integer of n -digits shall be denoted as $x = (x_{n-1}\dots x_1x_0)_\beta$ and represent the integer $x \equiv \sum_{i=0}^{n-1} x_i\beta^i$. The elements of the array x are said to be the radix β digits of the integer. For example, $x = (1, 2, 3)_{10}$ would represent the integer $1 \cdot 10^2 + 2 \cdot 10^1 + 3 \cdot 10^0 = 123$.

The term “mp_int” shall refer to a composite structure which contains the digits of the integer it represents, as well as auxiliary data required to manipulate the data. These additional members are discussed further in section 2.2.1. For the purposes of this text a “multiple precision integer” and an “mp_int” are assumed to be synonymous. When an algorithm is specified to accept an mp_int variable it is assumed the various auxiliary data members are present as well. An expression of the type *variablename.item* implies that it should evaluate to the member named “item” of the variable. For example, a string of characters may have a member “length” which would evaluate to the number of characters in the string. If the string a equals “hello” then it follows that $a.length = 5$.

For certain discussions more generic algorithms are presented to help the reader understand the final algorithm used to solve a given problem. When an algorithm is described as accepting an integer input it is assumed the input is a plain integer with no additional multiple-precision members. That is, algorithms that use integers as opposed to mp_ints as inputs do not concern themselves with the housekeeping operations required such as memory management. These algorithms will be used to establish the relevant theory which will subsequently be used to describe a multiple precision algorithm to solve the same problem.

1.3.2 Precision Notation

For the purposes of this text a single precision variable must be able to represent integers in the range $0 \leq x < q\beta$ while a double precision variable must be able to represent integers in the range $0 \leq x < q\beta^2$. The variable β represents the radix of a single digit of a multiple precision integer and must be of the form q^p for $q, p \in \mathbb{Z}^+$. The extra radix- q factor allows additions and subtractions to proceed without truncation of the carry. Since all modern computers are binary, it is assumed that q is two, for all intents and purposes.

Within the source code that will be presented for each algorithm, the data type **mp_digit** will represent a single precision integer type, while, the data type **mp_word** will represent a double precision integer type. In several algorithms

(notably the Comba routines) temporary results will be stored in arrays of double precision mp_words. For the purposes of this text x_j will refer to the j 'th digit of a single precision array and \hat{x}_j will refer to the j 'th digit of a double precision array. Whenever an expression is to be assigned to a double precision variable it is assumed that all single precision variables are promoted to double precision during the evaluation. Expressions that are assigned to a single precision variable are truncated to fit within the precision of a single precision data type.

For example, if $\beta = 10^2$ a single precision data type may represent a value in the range $0 \leq x < 10^3$, while a double precision data type may represent a value in the range $0 \leq x < 10^5$. Let $a = 23$ and $b = 49$ represent two single precision variables. The single precision product shall be written as $c \leftarrow a \cdot b$ while the double precision product shall be written as $\hat{c} \leftarrow a \cdot b$. In this particular case, $\hat{c} = 1127$ and $c = 127$. The most significant digit of the product would not fit in a single precision data type and as a result $c \neq \hat{c}$.

1.3.3 Algorithm Inputs and Outputs

Within the algorithm descriptions all variables are assumed to be scalars of either single or double precision as indicated. The only exception to this rule is when variables have been indicated to be of type mp_int. This distinction is important as scalars are often used as array indices and various other counters.

1.3.4 Mathematical Expressions

The $\lfloor \]$ brackets imply an expression truncated to an integer not greater than the expression itself. For example, $\lfloor 5.7 \rfloor = 5$. Similarly the $\lceil \]$ brackets imply an expression rounded to an integer not less than the expression itself. For example, $\lceil 5.1 \rceil = 6$. Typically when the $/$ division symbol is used the intention is to perform an integer division with truncation. For example, $5/2 = 2$ which will often be written as $\lfloor 5/2 \rfloor = 2$ for clarity. When an expression is written as a fraction a real value division is implied, for example $\frac{5}{2} = 2.5$.

The norm of a multiple precision integer, for example, $\|x\|$ will be used to represent the number of digits in the representation of the integer. For example, $\|123\| = 3$ and $\|79452\| = 5$.

1.3.5 Work Effort

To measure the efficiency of the specified algorithms, a modified big-Oh notation is used. In this system all single precision operations are considered to have the same cost⁸. That is a single precision addition, multiplication and division are assumed to take the same time to complete. While this is generally not true in practice, it will simplify the discussions considerably.

Some algorithms have slight advantages over others which is why some constants will not be removed in the notation. For example, a normal baseline multiplication (section 5.2.1) requires $O(n^2)$ work while a baseline squaring (section 5.3) requires $O(\frac{n^2+n}{2})$ work. In standard big-Oh notation these would both be said to be equivalent to $O(n^2)$. However, in the context of this text this is not the case as the magnitude of the inputs will typically be rather small. As a result small constant factors in the work effort will make an observable difference in algorithm efficiency.

All of the algorithms presented in this text have a polynomial time work level. That is, of the form $O(n^k)$ for $n, k \in \mathbb{Z}^+$. This will help make useful comparisons in terms of the speed of the algorithms and how various optimizations will help pay off in the long run.

1.4 Exercises

Within the more advanced chapters a section will be set aside to give the reader some challenging exercises related to the discussion at hand. These exercises are not designed to be prize winning problems, but instead to be thought provoking. Wherever possible the problems are forward minded, stating problems that will be answered in subsequent chapters. The reader is encouraged to finish the exercises as they appear to get a better understanding of the subject material.

That being said, the problems are designed to affirm knowledge of a particular subject matter. Students in particular are encouraged to verify they can answer the problems correctly before moving on.

Similar to the exercises of [1, pp. ix] these exercises are given a scoring system based on the difficulty of the problem. However, unlike [1] the problems do not get nearly as hard. The scoring of these exercises ranges from one (the easiest) to five (the hardest). The following table summarizes the scoring system used.

⁸Except where explicitly noted.

[1]	An easy problem that should only take the reader a manner of minutes to solve. Usually does not involve much computer time to solve.
[2]	An easy problem that involves a marginal amount of computer time usage. Usually requires a program to be written to solve the problem.
[3]	A moderately hard problem that requires a non-trivial amount of work. Usually involves trivial research and development of new theory from the perspective of a student.
[4]	A moderately hard problem that involves a non-trivial amount of work and research, the solution to which will demonstrate a higher mastery of the subject matter.
[5]	A hard problem that involves concepts that are difficult for a novice to solve. Solutions to these problems will demonstrate a complete mastery of the given subject.

Figure 1.2: Exercise Scoring System

Problems at the first level are meant to be simple questions that the reader can answer quickly without programming a solution or devising new theory. These problems are quick tests to see if the material is understood. Problems at the second level are also designed to be easy but will require a program or algorithm to be implemented to arrive at the answer. These two levels are essentially entry level questions.

Problems at the third level are meant to be a bit more difficult than the first two levels. The answer is often fairly obvious but arriving at an exacting solution requires some thought and skill. These problems will almost always involve devising a new algorithm or implementing a variation of another algorithm previously presented. Readers who can answer these questions will feel comfortable with the concepts behind the topic at hand.

Problems at the fourth level are meant to be similar to those of the level three questions except they will require additional research to be completed. The reader will most likely not know the answer right away, nor will the text provide the exact details of the answer until a subsequent chapter.

Problems at the fifth level are meant to be the hardest problems relative to all the other problems in the chapter. People who can correctly answer fifth level problems have a mastery of the subject matter at hand.

Often problems will be tied together. The purpose of this is to start a chain

of thought that will be discussed in future chapters. The reader is encouraged to answer the follow-up problems and try to draw the relevance of problems.

1.5 Introduction to LibTomMath

1.5.1 What is LibTomMath?

LibTomMath is a free and open source multiple precision integer library written entirely in portable ISO C. By portable it is meant that the library does not contain any code that is computer platform dependent or otherwise problematic to use on any given platform.

The library has been successfully tested under numerous operating systems including Unix⁹, MacOS, Windows, Linux, PalmOS and on standalone hardware such as the Gameboy Advance. The library is designed to contain enough functionality to be able to develop applications such as public key cryptosystems and still maintain a relatively small footprint.

1.5.2 Goals of LibTomMath

Libraries which obtain the most efficiency are rarely written in a high level programming language such as C. However, even though this library is written entirely in ISO C, considerable care has been taken to optimize the algorithm implementations within the library. Specifically the code has been written to work well with the GNU C Compiler (*GCC*) on both x86 and ARM processors. Wherever possible, highly efficient algorithms, such as Karatsuba multiplication, sliding window exponentiation and Montgomery reduction have been provided to make the library more efficient.

Even with the nearly optimal and specialized algorithms that have been included the Application Programming Interface (*API*) has been kept as simple as possible. Often generic place holder routines will make use of specialized algorithms automatically without the developer's specific attention. One such example is the generic multiplication algorithm `mp_mul()` which will automatically use Karatsuba, Toom-Cook, Comba or baseline multiplication based on the magnitude of the inputs and the configuration of the library.

Making LibTomMath as efficient as possible is not the only goal of the LibTomMath project. Ideally the library should be source compatible with another popular library which makes it more attractive for developers to use.

⁹All of these trademarks belong to their respective rightful owners.

In this case the MPI library was used as a API template for all the basic functions. MPI was chosen because it is another library that fits in the same niche as LibTomMath. Even though LibTomMath uses MPI as the template for the function names and argument passing conventions, it has been written from scratch by Tom St Denis.

The project is also meant to act as a learning tool for students, the logic being that no easy-to-follow “bignum” library exists which can be used to teach computer science students how to perform fast and reliable multiple precision integer arithmetic. To this end the source code has been given quite a few comments and algorithm discussion points.

1.6 Choice of LibTomMath

LibTomMath was chosen as the case study of this text not only because the author of both projects is one and the same but for more worthy reasons. Other libraries such as GMP [14], MPI [15], LIP [17] and OpenSSL [16] have multiple precision integer arithmetic routines but would not be ideal for this text for reasons that will be explained in the following sub-sections.

1.6.1 Code Base

The LibTomMath code base is all portable ISO C source code. This means that there are no platform dependent conditional segments of code littered throughout the source. This clean and uncluttered approach to the library means that a developer can more readily discern the true intent of a given section of source code without trying to keep track of what conditional code will be used.

The code base of LibTomMath is also well organized. Each function is in its own separate source code file which allows the reader to find a given function very quickly. On average there are about 76 lines of code per source file which makes the source very easily to follow. By comparison MPI and LIP are single file projects making code tracing very hard. GMP has many conditional code segments which also hinder tracing.

When compiled with GCC for the x86 processor and optimized for speed the entire library is approximately 66KiB¹⁰ which is fairly small compared to GMP (over 250KiB). LibTomMath is slightly larger than MPI (which compiles to about 50KiB) but LibTomMath is also much faster and more complete than MPI.

¹⁰The notation “KiB” means 2^{10} octets, similarly “MiB” means 2^{20} octets.

1.6.2 API Simplicity

LibTomMath is designed after the MPI library and shares the API design. Quite often programs that use MPI will build with LibTomMath without change. The function names correlate directly to the action they perform. Almost all of the functions share the same parameter passing convention. The learning curve is fairly shallow with the API provided which is an extremely valuable benefit for the student and developer alike.

The LIP library is an example of a library with an API that is awkward to work with. LIP uses function names that are often “compressed” to illegible short hand. LibTomMath does not share this characteristic.

The GMP library also does not return error codes. Instead it uses a POSIX.1 [?] signal system where errors are signaled to the host application. This happens to be the fastest approach but definitely not the most versatile. In effect a math error (i.e. invalid input, heap error, etc) can cause a program to stop functioning which is definitely undersireable in many situations.

1.6.3 Optimizations

While LibTomMath is certainly not the fastest library (GMP often beats LibTomMath by a factor of two) it does feature a set of optimal algorithms for tasks such as modular reduction, exponentiation, multiplication and squaring. GMP and LIP also feature such optimizations while MPI only uses baseline algorithms with no optimizations. GMP lacks a few of the additional modular reduction optimizations that LibTomMath features¹¹.

LibTomMath is almost always an order of magnitude faster than the MPI library at computationally expensive tasks such as modular exponentiation. In the grand scheme of “bignum” libraries LibTomMath is faster than the average library and usually slower than the best libraries such as GMP and OpenSSL by only a small factor.

1.6.4 Portability and Stability

LibTomMath will build “out of the box” on any platform equipped with a modern version of the GNU C Compiler (*GCC*). This means that without changes the library will build without configuration or setting up any variables. LIP and MPI will build “out of the box” as well but have numerous known bugs. Most

¹¹At the time of this writing GMP only had Barrett and Montgomery modular reduction algorithms.

notably the author of MPI has recently stopped working on his library and LIP has long since been discontinued.

GMP requires a configuration script to run and will not build out of the box. GMP and LibTomMath are still in active development and are very stable across a variety of platforms.

1.6.5 Choice

LibTomMath is a relatively compact, well documented, highly optimized and portable library which seems only natural for the case study of this text. Various source files from the LibTomMath project will be included within the text. However, the reader is encouraged to download their own copy of the library to actually be able to work with the library.

Chapter 2

Getting Started

2.1 Library Basics

The trick to writing any useful library of source code is to build a solid foundation and work outwards from it. First, a problem along with allowable solution parameters should be identified and analyzed. In this particular case the inability to accomodate multiple precision integers is the problem. Futhermore, the solution must be written as portable source code that is reasonably efficient across several different computer platforms.

After a foundation is formed the remainder of the library can be designed and implemented in a hierarchical fashion. That is, to implement the lowest level dependencies first and work towards the most abstract functions last. For example, before implementing a modular exponentiation algorithm one would implement a modular reduction algorithm. By building outwards from a base foundation instead of using a parallel design methodology the resulting project is highly modular. Being highly modular is a desirable property of any project as it often means the resulting product has a small footprint and updates are easy to perform.

Usually when I start a project I will begin with the header file. I define the data types I think I will need and prototype the initial functions that are not dependent on other functions (within the library). After I implement these base functions I prototype more dependent functions and implement them. The process repeats until I implement all of the functions I require. For example, in the case of LibTomMath I implemented functions such as `mp_init()` well before

I implemented `mp_mul()` and even further before I implemented `mp_exptmod()`. As an example as to why this design works note that the Karatsuba and Toom-Cook multipliers were written *after* the dependent function `mp_exptmod()` was written. Adding the new multiplication algorithms did not require changes to the `mp_exptmod()` function itself and lowered the total cost of ownership (*so to speak*) and of development for new algorithms. This methodology allows new algorithms to be tested in a complete framework with relative ease.

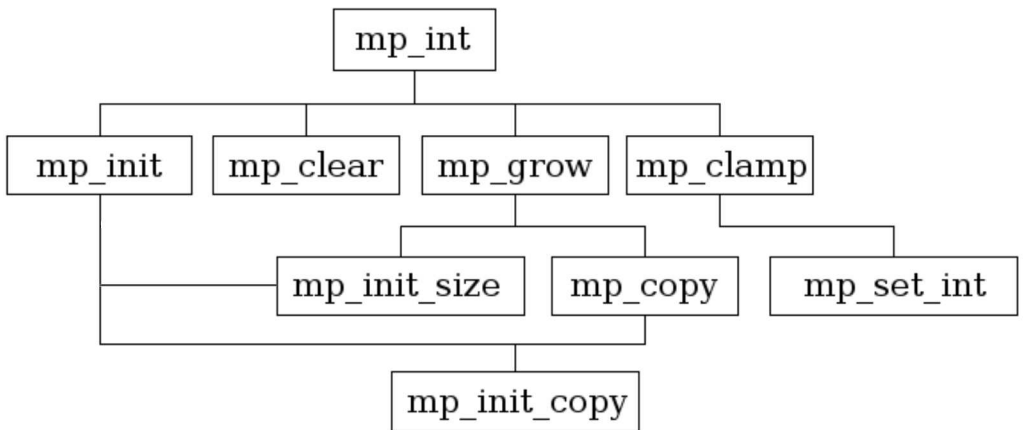


Figure 2.1: Design Flow of the First Few Original LibTomMath Functions.

Only after the majority of the functions were in place did I pursue a less hierarchical approach to auditing and optimizing the source code. For example, one day I may audit the multipliers and the next day the polynomial basis functions.

It only makes sense to begin the text with the preliminary data types and support algorithms required as well. This chapter discusses the core algorithms of the library which are the dependents for every other algorithm.

2.2 What is a Multiple Precision Integer?

Recall that most programming languages, in particular ISO C [18], only have fixed precision data types that on their own cannot be used to represent values

larger than their precision will allow. The purpose of multiple precision algorithms is to use fixed precision data types to create and manipulate multiple precision integers which may represent values that are very large.

As a well known analogy, school children are taught how to form numbers larger than nine by prepending more radix ten digits. In the decimal system the largest single digit value is 9. However, by concatenating digits together larger numbers may be represented. Newly prepended digits (*to the left*) are said to be in a different power of ten column. That is, the number 123 can be described as having a 1 in the hundreds column, 2 in the tens column and 3 in the ones column. Or more formally $123 = 1 \cdot 10^2 + 2 \cdot 10^1 + 3 \cdot 10^0$. Computer based multiple precision arithmetic is essentially the same concept. Larger integers are represented by adjoining fixed precision computer words with the exception that a different radix is used.

What most people probably do not think about explicitly are the various other attributes that describe a multiple precision integer. For example, the integer 154_{10} has two immediately obvious properties. First, the integer is positive, that is the sign of this particular integer is positive as opposed to negative. Second, the integer has three digits in its representation. There is an additional property that the integer possesses that does not concern pencil-and-paper arithmetic. The third property is how many digits placeholders are available to hold the integer.

The human analogy of this third property is ensuring there is enough space on the paper to write the integer. For example, if one starts writing a large number too far to the right on a piece of paper they will have to erase it and move left. Similarly, computer algorithms must maintain strict control over memory usage to ensure that the digits of an integer will not exceed the allowed boundaries. These three properties make up what is known as a multiple precision integer or `mp_int` for short.

2.2.1 The `mp_int` Structure

The `mp_int` structure is the ISO C based manifestation of what represents a multiple precision integer. The ISO C standard does not provide for any such data type but it does provide for making composite data types known as structures. The following is the structure definition used within LibTomMath.

```
typedef struct {
    int used, alloc, sign;
    mp_digit *dp;
```

```
} mp_int;
```

The `mp_int` structure can be broken down as follows.

1. The **used** parameter denotes how many digits of the array **dp** contain the digits used to represent a given integer. The **used** count must be positive (or zero) and may not exceed the **alloc** count.
2. The **alloc** parameter denotes how many digits are available in the array to use by functions before it has to increase in size. When the **used** count of a result would exceed the **alloc** count all of the algorithms will automatically increase the size of the array to accommodate the precision of the result.
3. The pointer **dp** points to a dynamically allocated array of digits that represent the given multiple precision integer. It is padded with (**alloc** – **used**) zero digits. The array is maintained in a least significant digit order. As a pencil and paper analogy the array is organized such that the right most digits are stored first starting at the location indexed by zero¹ in the array. For example, if **dp** contains $\{a, b, c, \dots\}$ where $\mathbf{dp}_0 = a$, $\mathbf{dp}_1 = b$, $\mathbf{dp}_2 = c, \dots$ then it would represent the integer $a + b\beta + c\beta^2 + \dots$.
4. The **sign** parameter denotes the sign as either zero/positive (**MP_ZPOS**) or negative (**MP_NEG**).

Valid `mp_int` Structures

Several rules are placed on the state of an `mp_int` structure and are assumed to be followed for reasons of efficiency. The only exceptions are when the structure is passed to initialization functions such as `mp_init()` and `mp_init_copy()`.

1. The value of **alloc** may not be less than one. That is **dp** always points to a previously allocated array of digits.
2. The value of **used** may not exceed **alloc** and must be greater than or equal to zero.
3. The value of **used** implies the digit at index $(used - 1)$ of the **dp** array is non-zero. That is, leading zero digits in the most significant positions must be trimmed.

¹In C all arrays begin at zero.

- (a) Digits in the **dp** array at and above the **used** location must be zero.
- 4. The value of **sign** must be **MP_ZPOS** if **used** is zero; this represents the `mp_int` value of zero.

2.3 Argument Passing

A convention of argument passing must be adopted early on in the development of any library. Making the function prototypes consistent will help eliminate many headaches in the future as the library grows to significant complexity. In LibTomMath the multiple precision integer functions accept parameters from left to right as pointers to `mp_int` structures. That means that the source (input) operands are placed on the left and the destination (output) on the right. Consider the following examples.

```
mp_mul(&a, &b, &c);    /* c = a * b */
mp_add(&a, &b, &a);    /* a = a + b */
mp_sqr(&a, &b);       /* b = a * a */
```

The left to right order is a fairly natural way to implement the functions since it lets the developer read aloud the functions and make sense of them. For example, the first function would read “multiply a and b and store in c”.

Certain libraries (*LIP by Lenstra for instance*) accept parameters the other way around, to mimic the order of assignment expressions. That is, the destination (output) is on the left and arguments (inputs) are on the right. In truth, it is entirely a matter of preference. In the case of LibTomMath the convention from the MPI library has been adopted.

Another very useful design consideration, provided for in LibTomMath, is whether to allow argument sources to also be a destination. For example, the second example (*mp_add*) adds *a* to *b* and stores in *a*. This is an important feature to implement since it allows the calling functions to cut down on the number of variables it must maintain. However, to implement this feature specific care has to be given to ensure the destination is not modified before the source is fully read.

2.4 Return Values

A well implemented application, no matter what its purpose, should trap as many runtime errors as possible and return them to the caller. By catching

runtime errors a library can be guaranteed to prevent undefined behaviour. However, the end developer can still manage to cause a library to crash. For example, by passing an invalid pointer an application may fault by dereferencing memory not owned by the application.

In the case of LibTomMath the only errors that are checked for are related to inappropriate inputs (division by zero for instance) and memory allocation errors. It will not check that the `mp_int` passed to any function is valid nor will it check pointers for validity. Any function that can cause a runtime error will return an error code as an `int` data type with one of the following values.

Value	Meaning
<code>MP_OKAY</code>	The function was successful
<code>MP_VAL</code>	One of the input value(s) was invalid
<code>MP_MEM</code>	The function ran out of heap memory

When an error is detected within a function it should free any memory it allocated, often during the initialization of temporary `mp_ints`, and return as soon as possible. The goal is to leave the system in the same state it was when the function was called. Error checking with this style of API is fairly simple.

```
int err;
if ((err = mp_add(&a, &b, &c)) != MP_OKAY) {
    printf("Error: %s\n", mp_error_to_string(err));
    exit(EXIT_FAILURE);
}
```

The GMP [14] library uses C style *signals* to flag errors which is of questionable use. Not all errors are fatal and it was not deemed ideal by the author of LibTomMath to force developers to have signal handlers for such cases.

2.5 Initialization and Clearing

The logical starting point when actually writing multiple precision integer functions is the initialization and clearing of the `mp_int` structures. These two algorithms will be used by the majority of the higher level algorithms.

Given the basic `mp_int` structure an initialization routine must first allocate memory to hold the digits of the integer. Often it is optimal to allocate a sufficiently large pre-set number of digits even though the initial integer will

represent zero. If only a single digit were allocated quite a few subsequent re-allocations would occur when operations are performed on the integers. There is a tradeoff between how many default digits to allocate and how many re-allocations are tolerable. Obviously allocating an excessive amount of digits initially will waste memory and become unmanageable.

If the memory for the digits has been successfully allocated then the rest of the members of the structure must be initialized. Since the initial state of an `mp_int` is to represent the zero integer, the allocated digits must be set to zero. The **used** count set to zero and **sign** set to `MP_ZPOS`.

2.5.1 Initializing an `mp_int`

An `mp_int` is said to be initialized if it is set to a valid, preferably default, state such that all of the members of the structure are set to valid values. The `mp_init` algorithm will perform such an action.

Algorithm **mp_init**.

Input. An `mp_int` a

Output. Allocate memory and initialize a to a known valid `mp_int` state.

1. Allocate memory for `MP_PREC` digits.
 2. If the allocation failed return(`MP_MEM`)
 3. for n from 0 to $MP_PREC - 1$ do
 - 3.1 $a_n \leftarrow 0$
 4. $a.sign \leftarrow MP_ZPOS$
 5. $a.used \leftarrow 0$
 6. $a.alloc \leftarrow MP_PREC$
 7. Return(`MP_OKAY`)
-

Figure 2.2: Algorithm `mp_init`

Algorithm `mp_init`. The `MP_PREC` name represents a constant² used to dictate the minimum precision of allocated `mp_int` integers. Ideally, it is at least equal to 32 since for most purposes that will be more than enough.

Memory for the default number of digits is allocated first. If the allocation fails the algorithm returns immediately with the `MP_MEM` error code. If

²Defined in the “`tommath.h`” header file within `LibTomMath`.

the allocation succeeds the remaining members of the `mp_int` structure must be initialized to reflect the default initial state.

The allocated digits are all set to zero (step three) to ensure they are in a known state. The **sign**, **used** and **alloc** are subsequently initialized to represent the zero integer. By step seven the algorithm returns a success code and the `mp_int` a has been successfully initialized to a valid state representing the integer zero.

Remark. This function introduces the idiosyncrasy that all iterative loops, commonly initiated with the “for” keyword, iterate incrementally when the “to” keyword is placed between two expressions. For example, “for a from b to c do” means that a subsequent expression (or body of expressions) are to be evaluated upto $c - b$ times so long as $b \leq c$. In each iteration the variable a is substituted for a new integer that lies inclusively between b and c . If $b > c$ occurred the loop would not iterate. By contrast if the “downto” keyword were used in place of “to” the loop would iterate decrementally.

File: `bn_mp_init.c`

```

016
017  /* init a new bigint */
018  int mp_init (mp_int * a)
019  {
020  /* allocate memory required and clear it */
021  a->dp = OPT_CAST XCALLOC (sizeof (mp_digit), MP_PREC);
022  if (a->dp == NULL) {
023      return MP_MEM;
024  }
025
026  /* set the used to zero, allocated digits to the default precision
027   * and sign to positive */
028  a->used = 0;
029  a->alloc = MP_PREC;
030  a->sign = MP_ZPOS;
031
032  return MP_OKAY;
033  }
```

One immediate observation of this initialization function is that it does not return a pointer to a `mp_int` structure. It is assumed that the caller has already allocated memory for the `mp_int` structure, typically on the application stack. The call to `mp_init()` is used only to initialize the members of the structure to a known default state.

Before any of the other members of the structure are initialized memory from the application heap is allocated with the `calloc()` function (line @22,calloc@). The size of the allocated memory is large enough to hold `MP_PREC` `mp_digit` variables. The `calloc()` function is used instead³ of `malloc()` since digits have to be set to zero for the function to finish correctly. The `OPT_CAST` token is a macro definition which will turn into a cast from `void *` to `mp_digit *` for C++ compilers. It is not required for C compilers.

After the memory has been successfully allocated the remainder of the members are initialized (lines 28 through 30) to their respective default states. At this point the algorithm has succeeded and a success code is returned to the calling function.

If this function returns `MP_OKAY` it is safe to assume the `mp_int` structure has been properly initialized and is safe to use with other functions within the library.

2.5.2 Clearing an `mp_int`

When an `mp_int` is no longer required by the application, the memory that has been allocated for its digits must be returned to the application's memory pool with the `mp_clear` algorithm.

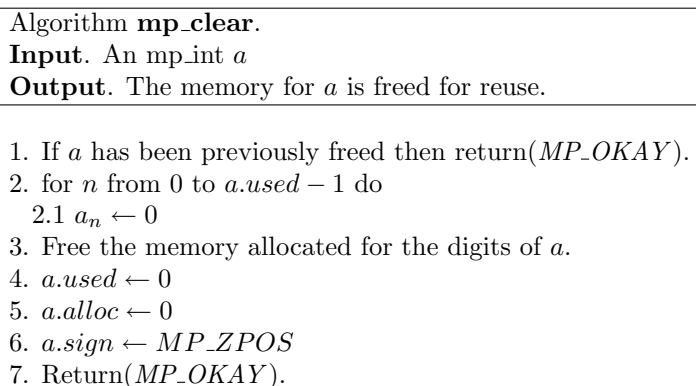


Figure 2.3: Algorithm `mp_clear`

³`calloc()` will allocate memory in the same manner as `malloc()` except that it also sets the contents to zero upon successfully allocating the memory.

Algorithm mp_clear. This algorithm releases the memory allocated for an mp_int back into the memory pool for reuse. It is designed such that a given mp_int structure can be cleared multiple times between initializations without attempting to free the memory twice⁴.

The first step determines if the mp_int structure has been marked as free already. If it has, the algorithm returns success immediately as no further actions are required. Otherwise, the algorithm will proceed to put the structure in a known empty and otherwise invalid state. First the digits of the mp_int are set to zero. The memory that has been allocated for the digits is then freed. The **used** and **alloc** counts are both set to zero and the **sign** set to **MP_ZPOS**. This known fixed state for cleared mp_int structures will make debugging easier for the end developer. That is, if they spot (via their debugger) an mp_int they are using that is in this state it will be obvious that they erroneously and prematurely cleared the mp_int structure.

Note that once an mp_int has been cleared the mp_int structure is no longer in a valid state for any other algorithm with the exception of algorithms mp_init, mp_init_copy, mp_init_size and mp_clear.

File: bn_mp_clear.c

```

016
017  /* clear one (frees) */
018  void
019  mp_clear (mp_int * a)
020  {
021      /* only do anything if a hasn't been freed previously */
022      if (a->dp != NULL) {
023          /* first zero the digits */
024          memset (a->dp, 0, sizeof (mp_digit) * a->used);
025
026          /* free ram */
027          XFREE(a->dp);
028
029          /* reset members to make debugging easier */
030          a->dp = NULL;
031          a->alloc = a->used = 0;
032          a->sign = MP_ZPOS;
033      }
034  }
```

⁴In ISO C for example, calling free() twice on the same memory block causes undefined behaviour.

The “if” statement (line 22) prevents the heap from being corrupted if a user double-frees an `mp_int`. This is because once the memory is freed the pointer is set to **NULL** (line 30).

Without the check, code that accidentally calls `mp_clear` twice for a given `mp_int` structure would try to free the memory allocated for the digits twice. This may cause some C libraries to signal a fault. By setting the pointer to **NULL** it helps debug code that may inadvertently free the `mp_int` before it is truly not needed, because attempts to reference digits should fail immediately. The allocated digits are set to zero before being freed (line 24). This is ideal for cryptographic situations where the integer that the `mp_int` represents might need to be kept a secret.

2.6 Maintenance Algorithms

The previous sections describes how to initialize and clear an `mp_int` structure. To further support operations that are to be performed on `mp_int` structures (such as addition and multiplication) the dependent algorithms must be able to augment the precision of an `mp_int` and initialize `mp_ints` with differing initial conditions.

These algorithms complete the set of low level algorithms required to work with `mp_int` structures in the higher level algorithms such as addition, multiplication and modular exponentiation.

2.6.1 Augmenting an `mp_int`'s Precision

When storing a value in an `mp_int` structure, a sufficient number of digits must be available to accomodate the entire result of an operation without loss of precision. Quite often the size of the array given by the **alloc** member is large enough to simply increase the **used** digit count. However, when the size of the array is too small it must be re-sized appropriately to accomodate the result. The `mp_grow` algorithm will provide this functionality.

Algorithm **mp_grow**.

Input. An mp_int a and an integer b .

Output. a is expanded to accomodate b digits.

1. if $a.alloc \geq b$ then return(MP_OKAY)
 2. $u \leftarrow b \pmod{MP_PREC}$
 3. $v \leftarrow b + 2 \cdot MP_PREC - u$
 4. Re-Allocate the array of digits a to size v
 5. If the allocation failed then return(MP_MEM).
 6. for n from $a.alloc$ to $v - 1$ do
 - 6.1 $a_n \leftarrow 0$
 7. $a.alloc \leftarrow v$
 8. Return(MP_OKAY)
-

Figure 2.4: Algorithm mp_grow

Algorithm mp_grow. It is ideal to prevent re-allocations from being performed if they are not required (step one). This is useful to prevent mp_ints from growing excessively in code that erroneously calls mp_grow.

The requested digit count is padded up to next multiple of **MP_PREC** plus an additional **MP_PREC** (steps two and three). This helps prevent many trivial reallocations that would grow an mp_int by trivially small values.

It is assumed that the reallocation (step four) leaves the lower $a.alloc$ digits of the mp_int intact. This is much akin to how the *realloc* function from the standard C library works. Since the newly allocated digits are assumed to contain undefined values they are initially set to zero.

File: bn_mp_grow.c

```

016
017  /* grow as required */
018  int mp_grow (mp_int * a, int size)
019  {
020      int    i;
021      mp_digit *tmp;
022
023      /* if the alloc size is smaller alloc more ram */
024      if (a->alloc < size) {
025          /* ensure there are always at least MP_PREC digits extra on top */
026          size += (MP_PREC * 2) - (size % MP_PREC);
027

```

```

028     /* reallocate the array a->dp
029     *
030     * We store the return in a temporary variable
031     * in case the operation failed we don't want
032     * to overwrite the dp member of a.
033     */
034     tmp = OPT_CAST XREALLOC (a->dp, sizeof (mp_digit) * size);
035     if (tmp == NULL) {
036         /* reallocation failed but "a" is still valid [can be freed] */
037         return MP_MEM;
038     }
039
040     /* reallocation succeeded so set a->dp */
041     a->dp = tmp;
042
043     /* zero excess digits */
044     i      = a->alloc;
045     a->alloc = size;
046     for (; i < a->alloc; i++) {
047         a->dp[i] = 0;
048     }
049 }
050 return MP_OKAY;
051 }

```

The first step is to see if we actually need to perform a re-allocation at all (line 24). If a reallocation must occur the digit count is padded upwards to help prevent many trivial reallocations (line 26). Next the reallocation is performed and the return of `realloc()` is stored in a temporary pointer named `tmp` (line 36). The return is stored in a temporary instead of `a.dp` to prevent the code from losing the original pointer in case the reallocation fails. Had the return been stored in `a.dp` instead there would be no way to reclaim the heap originally used.

If the reallocation fails the function will return **MP_MEM** (line 37), otherwise, the value of `tmp` is assigned to the pointer `a.dp` and the function continues. A simple for loop from line 46 to line 51 will zero all digits that were above the old **alloc** limit to make sure the integer is in a known state.

2.6.2 Initializing Variable Precision mp_ints

Occasionally the number of digits required will be known in advance of an initialization, based on, for example, the size of input mp_ints to a given algorithm. The purpose of algorithm mp_init_size is similar to mp_init except that it will allocate *at least* a specified number of digits.

Algorithm **mp_init_size**.
Input. An mp_int a and the requested number of digits b .
Output. a is initialized to hold at least b digits.

1. $u \leftarrow b \pmod{MP_PREC}$
2. $v \leftarrow b + 2 \cdot MP_PREC - u$
3. Allocate v digits.
4. for n from 0 to $v - 1$ do
 - 4.1 $a_n \leftarrow 0$
5. $a.sign \leftarrow MP_ZPOS$
6. $a.used \leftarrow 0$
7. $a.alloc \leftarrow v$
8. Return(MP_OKAY)

Figure 2.5: Algorithm mp_init_size

Algorithm mp_init_size. This algorithm will initialize an mp_int structure a like algorithm mp_init with the exception that the number of digits allocated can be controlled by the second input argument b . The input size is padded upwards so it is a multiple of **MP_PREC** plus an additional **MP_PREC** digits. This padding is used to prevent trivial allocations from becoming a bottleneck in the rest of the algorithms.

Like algorithm mp_init, the mp_int structure is initialized to a default state representing the integer zero. This particular algorithm is useful if it is known ahead of time the approximate size of the input. If the approximation is correct no further memory re-allocations are required to work with the mp_int.

```

File: bn_mp_init_size.c
016
017  /* init an mp_init for a given size */
018  int mp_init_size (mp_int * a, int size)
019  {
020      /* pad size so there are always extra digits */
021      size += (MP_PREC * 2) - (size % MP_PREC);

```

```

022
023     /* alloc mem */
024     a->dp = OPT_CAST XCALLOC (sizeof (mp_digit), size);
025     if (a->dp == NULL) {
026         return MP_MEM;
027     }
028     a->used = 0;
029     a->alloc = size;
030     a->sign = MP_ZPOS;
031
032     return MP_OKAY;
033 }

```

The number of digits b requested is padded (line 21) by first augmenting it to the next multiple of **MP_PREC** and then adding **MP_PREC** to the result. If the memory can be successfully allocated the `mp_int` is placed in a default state representing the integer zero. Otherwise, the error code **MP_MEM** will be returned (line 26).

The digits are allocated and set to zero at the same time with the `calloc()` function (line @25,calloc@). The **used** count is set to zero, the **alloc** count set to the padded digit count and the **sign** flag set to **MP_ZPOS** to achieve a default valid `mp_int` state (lines 28, 29 and 30). If the function returns successfully then it is correct to assume that the `mp_int` structure is in a valid state for the remainder of the functions to work with.

2.6.3 Multiple Integer Initializations and Clearings

Occasionally a function will require a series of `mp_int` data types to be made available simultaneously. The purpose of algorithm `mp_init_multi` is to initialize a variable length array of `mp_int` structures in a single statement. It is essentially a shortcut to multiple initializations.

Algorithm **mp_init_multi**.

Input. Variable length array V_k of mp_int variables of length k .

Output. The array is initialized such that each mp_int of V_k is ready to use.

1. for n from 0 to $k - 1$ do
 - 1.1. Initialize the mp_int V_n (*mp_init*)
 - 1.2. If initialization failed then do
 - 1.2.1. for j from 0 to n do
 - 1.2.1.1. Free the mp_int V_j (*mp_clear*)
 - 1.2.2. Return(*MP_MEM*)
 2. Return(*MP_OKAY*)
-

Figure 2.6: Algorithm mp_init_multi

Algorithm mp_init_multi. The algorithm will initialize the array of mp_int variables one at a time. If a runtime error has been detected (*step 1.2*) all of the previously initialized variables are cleared. The goal is an “all or nothing” initialization which allows for quick recovery from runtime errors.

File: bn_mp_init_multi.c

```

016  #include <stdarg.h>
017
018  int mp_init_multi(mp_int *mp, ...)
019  {
020      mp_err res = MP_OKAY;      /* Assume ok until proven otherwise */
021      int n = 0;                 /* Number of ok inits */
022      mp_int* cur_arg = mp;
023      va_list args;
024
025      va_start(args, mp);       /* init args to next argument from caller */
026      while (cur_arg != NULL) {
027          if (mp_init(cur_arg) != MP_OKAY) {
028              /* Oops - error! Back-track and mp_clear what we already
029               succeeded in init-ing, then return error.
030              */
031              va_list clean_args;
032
033              /* end the current list */
034              va_end(args);
035

```

```

036         /* now start cleaning up */
037         cur_arg = mp;
038         va_start(clean_args, mp);
039         while (n--) {
040             mp_clear(cur_arg);
041             cur_arg = va_arg(clean_args, mp_int*);
042         }
043         va_end(clean_args);
044         res = MP_MEM;
045         break;
046     }
047     n++;
048     cur_arg = va_arg(args, mp_int*);
049 }
050 va_end(args);
051 return res;          /* Assumed ok, if error flagged above. */
052 }
053

```

This function initializes a variable length list of `mp_int` structure pointers. However, instead of having the `mp_int` structures in an actual C array they are simply passed as arguments to the function. This function makes use of the “...” argument syntax of the C programming language. The list is terminated with a final **NULL** argument appended on the right.

The function uses the “`stdarg.h`” *va* functions to step portably through the arguments to the function. A count n of successfully initialized `mp_int` structures is maintained (line 47) such that if a failure does occur, the algorithm can backtrack and free the previously initialized structures (lines 27 to 46).

2.6.4 Clamping Excess Digits

When a function anticipates a result will be n digits it is simpler to assume this is true within the body of the function instead of checking during the computation. For example, a multiplication of a i digit number by a j digit produces a result of at most $i + j$ digits. It is entirely possible that the result is $i + j - 1$ though, with no final carry into the last position. However, suppose the destination had to be first expanded (*via* `mp_grow`) to accommodate $i + j - 1$ digits than further expanded to accommodate the final carry. That would be a considerable waste of time since heap operations are relatively slow.

The ideal solution is to always assume the result is $i + j$ and fix up the **used** count after the function terminates. This way a single heap operation (*at most*)

is required. However, if the result was not checked there would be an excess high order zero digit.

For example, suppose the product of two integers was $x_n = (0x_{n-1}x_{n-2}\dots x_0)_\beta$. The leading zero digit will not contribute to the precision of the result. In fact, through subsequent operations more leading zero digits would accumulate to the point the size of the integer would be prohibitive. As a result even though the precision is very low the representation is excessively large.

The `mp_clamp` algorithm is designed to solve this very problem. It will trim high-order zeros by decrementing the **used** count until a non-zero most significant digit is found. Also in this system, zero is considered to be a positive number which means that if the **used** count is decremented to zero, the sign must be set to **MP_ZPOS**.

Algorithm **mp_clamp**.
Input. An `mp_int` a
Output. Any excess leading zero digits of a are removed

1. while $a.used > 0$ and $a_{a.used-1} = 0$ do
 - 1.1 $a.used \leftarrow a.used - 1$
2. if $a.used = 0$ then do
 - 2.1 $a.sign \leftarrow MP_ZPOS$

Figure 2.7: Algorithm `mp_clamp`

Algorithm `mp_clamp`. As can be expected this algorithm is very simple. The loop on step one is expected to iterate only once or twice at the most. For example, this will happen in cases where there is not a carry to fill the last position. Step two fixes the sign for when all of the digits are zero to ensure that the `mp_int` is valid at all times.

File: `bn_mp_clamp.c`

```

016
017 /* trim unused digits
018 *
019 * This is used to ensure that leading zero digits are
020 * trimmed and the leading "used" digit will be non-zero
021 * Typically very fast. Also fixes the sign if there
022 * are no more leading digits

```



```
023  */
024  void
025  mp_clamp (mp_int * a)
026  {
027      /* decrease used while the most significant digit is
028       * zero.
029       */
030      while (a->used > 0 && a->dp[a->used - 1] == 0) {
031          --(a->used);
032      }
033
034      /* reset the sign flag if used == 0 */
035      if (a->used == 0) {
036          a->sign = MP_ZPOS;
037      }
038  }
```

Note on line 27 how to test for the **used** count is made on the left of the `&&` operator. In the C programming language the terms to `&&` are evaluated left to right with a boolean short-circuit if any condition fails. This is important since if the **used** is zero the test on the right would fetch below the array. That is obviously undesirable. The parenthesis on line 30 is used to make sure the **used** count is decremented and not the pointer “a”.

Exercises

- [1] Discuss the relevance of the **used** member of the `mp_int` structure.
- [1] Discuss the consequences of not using padding when performing allocations.
- [2] Estimate an ideal value for **MP_PREC** when performing 1024-bit RSA encryption when $\beta = 2^{28}$.
- [1] Discuss the relevance of the algorithm `mp_clamp`. What does it prevent?
- [1] Give an example of when the algorithm `mp_init_copy` might be useful.

Chapter 3

Basic Operations

3.1 Introduction

In the previous chapter a series of low level algorithms were established that dealt with initializing and maintaining `mp_int` structures. This chapter will discuss another set of seemingly non-algebraic algorithms which will form the low level basis of the entire library. While these algorithm are relatively trivial it is important to understand how they work before proceeding since these algorithms will be used almost intrinsically in the following chapters.

The algorithms in this chapter deal primarily with more “programmer” related tasks such as creating copies of `mp_int` structures, assigning small values to `mp_int` structures and comparisons of the values `mp_int` structures represent.

3.2 Assigning Values to `mp_int` Structures

3.2.1 Copying an `mp_int`

Assigning the value that a given `mp_int` structure represents to another `mp_int` structure shall be known as making a copy for the purposes of this text. The copy of the `mp_int` will be a separate entity that represents the same value as the `mp_int` it was copied from. The `mp_copy` algorithm provides this functionality.

Algorithm **mp_copy**.

Input. An mp_int a and b .

Output. Store a copy of a in b .

1. If $b.alloc < a.used$ then grow b to $a.used$ digits. (*mp_grow*)
 2. for n from 0 to $a.used - 1$ do
 - 2.1 $b_n \leftarrow a_n$
 3. for n from $a.used$ to $b.used - 1$ do
 - 3.1 $b_n \leftarrow 0$
 4. $b.used \leftarrow a.used$
 5. $b.sign \leftarrow a.sign$
 6. return(*MP_OKAY*)
-

Figure 3.1: Algorithm mp_copy

Algorithm mp_copy. This algorithm copies the mp_int a such that upon successful termination of the algorithm the mp_int b will represent the same integer as the mp_int a . The mp_int b shall be a complete and distinct copy of the mp_int a meaning that the mp_int a can be modified and it shall not affect the value of the mp_int b .

If b does not have enough room for the digits of a it must first have its precision augmented via the mp_grow algorithm. The digits of a are copied over the digits of b and any excess digits of b are set to zero (step two and three). The **used** and **sign** members of a are finally copied over the respective members of b .

Remark. This algorithm also introduces a new idiosyncrasy that will be used throughout the rest of the text. The error return codes of other algorithms are not explicitly checked in the pseudo-code presented. For example, in step one of the mp_copy algorithm the return of mp_grow is not explicitly checked to ensure it succeeded. Text space is limited so it is assumed that if a algorithm fails it will clear all temporarily allocated mp_ints and return the error code itself. However, the C code presented will demonstrate all of the error handling logic required to implement the pseudo-code.

File: bn_mp_copy.c

```

016
017  /* copy, b = a */
018  int
019  mp_copy (mp_int * a, mp_int * b)

```

```
020  {
021     int     res, n;
022
023     /* if dst == src do nothing */
024     if (a == b) {
025         return MP_OKAY;
026     }
027
028     /* grow dest */
029     if (b->alloc < a->used) {
030         if ((res = mp_grow (b, a->used)) != MP_OKAY) {
031             return res;
032         }
033     }
034
035     /* zero b and copy the parameters over */
036     {
037         register mp_digit *tmpa, *tmpb;
038
039         /* pointer aliases */
040
041         /* source */
042         tmpa = a->dp;
043
044         /* destination */
045         tmpb = b->dp;
046
047         /* copy all the digits */
048         for (n = 0; n < a->used; n++) {
049             *tmpb++ = *tmpa++;
050         }
051
052         /* clear high digits */
053         for (; n < b->used; n++) {
054             *tmpb++ = 0;
055         }
056     }
057
058     /* copy used count and sign */
059     b->used = a->used;
060     b->sign = a->sign;
061     return MP_OKAY;
```

```
062 }
```

Occasionally a dependent algorithm may copy an `mp_int` effectively into itself such as when the input and output `mp_int` structures passed to a function are one and the same. For this case it is optimal to return immediately without copying digits (line 24).

The `mp_int` b must have enough digits to accommodate the used digits of the `mp_int` a . If $b.alloc$ is less than $a.used$ the algorithm `mp_grow` is used to augment the precision of b (lines 29 to 33). In order to simplify the inner loop that copies the digits from a to b , two aliases $tmpa$ and $tmpb$ point directly at the digits of the `mp_ints` a and b respectively. These aliases (lines 42 and 45) allow the compiler to access the digits without first dereferencing the `mp_int` pointers and then subsequently the pointer to the digits.

After the aliases are established the digits from a are copied into b (lines 48 to 50) and then the excess digits of b are set to zero (lines 53 to 55). Both “for” loops make use of the pointer aliases and in fact the alias for b is carried through into the second “for” loop to clear the excess digits. This optimization allows the alias to stay in a machine register fairly easy between the two loops.

Remarks. The use of pointer aliases is an implementation methodology first introduced in this function that will be used considerably in other functions. Technically, a pointer alias is simply a short hand alias used to lower the number of pointer dereferencing operations required to access data. For example, a for loop may resemble

```
for (x = 0; x < 100; x++) {
    a->num[4]->dp[x] = 0;
}
```

This could be re-written using aliases as

```
mp_digit *tmpa;
a = a->num[4]->dp;
for (x = 0; x < 100; x++) {
    *a++ = 0;
}
```

In this case an alias is used to access the array of digits within an `mp_int` structure directly. It may seem that a pointer alias is strictly not required as a compiler may optimize out the redundant pointer operations. However, there are two dominant reasons to use aliases.

The first reason is that most compilers will not effectively optimize pointer arithmetic. For example, some optimizations may work for the Microsoft Visual C++ compiler (MSVC) and not for the GNU C Compiler (GCC). Also some optimizations may work for GCC and not MSVC. As such it is ideal to find a common ground for as many compilers as possible. Pointer aliases optimize the code considerably before the compiler even reads the source code which means the end compiled code stands a better chance of being faster.

The second reason is that pointer aliases often can make an algorithm simpler to read. Consider the first “for” loop of the function `mp_copy()` re-written to not use pointer aliases.

```
/* copy all the digits */
for (n = 0; n < a->used; n++) {
    b->dp[n] = a->dp[n];
}
```

Whether this code is harder to read depends strongly on the individual. However, it is quantifiably slightly more complicated as there are four variables within the statement instead of just two.

Nested Statements

Another commonly used technique in the source routines is that certain sections of code are nested. This is used in particular with the pointer aliases to highlight code phases. For example, a Comba multiplier (discussed in chapter six) will typically have three different phases. First the temporaries are initialized, then the columns calculated and finally the carries are propagated. In this example the middle column production phase will typically be nested as it uses temporary variables and aliases the most.

The nesting also simplifies the source code as variables that are nested are only valid for their scope. As a result the various temporary variables required do not propagate into other sections of code.

3.2.2 Creating a Clone

Another common operation is to make a local temporary copy of an `mp_int` argument. To initialize an `mp_int` and then copy another existing `mp_int` into the newly intialized `mp_int` will be known as creating a clone. This is useful within functions that need to modify an argument but do not wish to actually

modify the original copy. The `mp_init_copy` algorithm has been designed to help perform this task.

Algorithm `mp_init_copy`.
Input. An `mp_int` a and b
Output. a is initialized to be a copy of b .

1. Init a . (*mp_init*)
2. Copy b to a . (*mp_copy*)
3. Return the status of the copy operation.

Figure 3.2: Algorithm `mp_init_copy`

Algorithm `mp_init_copy`. This algorithm will initialize an `mp_int` variable and copy another previously initialized `mp_int` variable into it. As such this algorithm will perform two operations in one step.

```
File: bn_mp_init_copy.c
016
017 /* creates "a" then copies b into it */
018 int mp_init_copy (mp_int * a, mp_int * b)
019 {
020     int     res;
021
022     if ((res = mp_init (a)) != MP_OKAY) {
023         return res;
024     }
025     return mp_copy (b, a);
026 }
```

This will initialize **a** and make it a verbatim copy of the contents of **b**. Note that **a** will have its own memory allocated which means that **b** may be cleared after the call and **a** will be left intact.

3.3 Zeroing an Integer

Resetting an `mp_int` to the default state is a common step in many algorithms. The `mp_zero` algorithm will be the algorithm used to perform this task.

Algorithm `mp_zero`. This algorithm simply resets a `mp_int` to the default state.

Algorithm **mp_zero**.
Input. An mp_int a
Output. Zero the contents of a

1. $a.used \leftarrow 0$
2. $a.sign \leftarrow MP_ZPOS$
3. for n from 0 to $a.alloc - 1$ do
 - 3.1 $a_n \leftarrow 0$

Figure 3.3: Algorithm mp_zero

File: bn_mp_zero.c

```

016
017  /* set to zero */
018  void
019  mp_zero (mp_int * a)
020  {
021      a->sign = MP_ZPOS;
022      a->used = 0;
023      memset (a->dp, 0, sizeof (mp_digit) * a->alloc);
024  }
```

After the function is completed, all of the digits are zeroed, the **used** count is zeroed and the **sign** variable is set to **MP_ZPOS**.

3.4 Sign Manipulation

3.4.1 Absolute Value

With the mp_int representation of an integer, calculating the absolute value is trivial. The mp_abs algorithm will compute the absolute value of an mp_int.

Algorithm **mp_abs**.

Input. An mp_int a

Output. Computes $b = |a|$

1. Copy a to b . (*mp_copy*)
 2. If the copy failed return(*MP_MEM*).
 3. $b.sign \leftarrow MP_ZPOS$
 4. Return(*MP_OKAY*)
-

Figure 3.4: Algorithm mp_abs

Algorithm mp_abs. This algorithm computes the absolute of an mp_int input. First it copies a over b . This is an example of an algorithm where the check in mp_copy that determines if the source and destination are equal proves useful. This allows, for instance, the developer to pass the same mp_int as the source and destination to this function without addition logic to handle it.

File: bn_mp_abs.c

```

016
017  /* b = |a|
018   *
019   * Simple function copies the input and fixes the sign to positive
020   */
021  int
022  mp_abs (mp_int * a, mp_int * b)
023  {
024      int    res;
025
026      /* copy a to b */
027      if (a != b) {
028          if ((res = mp_copy (a, b)) != MP_OKAY) {
029              return res;
030          }
031      }
032
033      /* force the sign of b to positive */
034      b->sign = MP_ZPOS;
035
036      return MP_OKAY;
037  }
```

3.4.2 Integer Negation

With the `mp_int` representation of an integer, calculating the negation is also trivial. The `mp_neg` algorithm will compute the negative of an `mp_int` input.

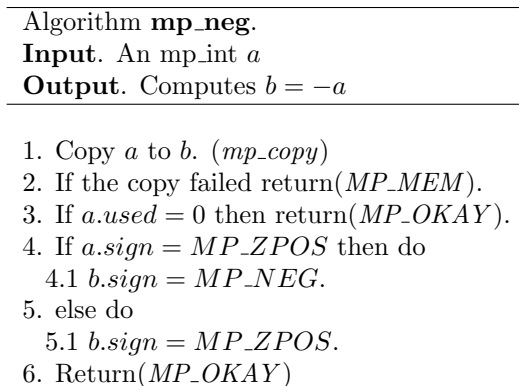


Figure 3.5: Algorithm `mp_neg`

Algorithm `mp_neg`. This algorithm computes the negation of an input. First it copies a over b . If a has no used digits then the algorithm returns immediately. Otherwise it flips the sign flag and stores the result in b . Note that if a had no digits then it must be positive by definition. Had step three been omitted then the algorithm would return zero as negative.

File: `bn_mp_neg.c`

```

016
017  /* b = -a */
018  int mp_neg (mp_int * a, mp_int * b)
019  {
020      int    res;
021      if ((res = mp_copy (a, b)) != MP_OKAY) {
022          return res;
023      }
024      if (mp_iszero(b) != 1) {
025          b->sign = (a->sign == MP_ZPOS) ? MP_NEG : MP_ZPOS;
026      }
027      return MP_OKAY;
028  }
```

3.5 Small Constants

3.5.1 Setting Small Constants

Often a `mp_int` must be set to a relatively small value such as 1 or 2. For these cases the `mp_set` algorithm is useful.

Algorithm **mp_set**.
Input. An `mp_int` a and a digit b
Output. Make a equivalent to b

1. Zero a (`mp_zero`).
2. $a_0 \leftarrow b \pmod{\beta}$
3. $a.\text{used} \leftarrow \begin{cases} 1 & \text{if } a_0 > 0 \\ 0 & \text{if } a_0 = 0 \end{cases}$

Figure 3.6: Algorithm `mp_set`

Algorithm `mp_set`. This algorithm sets a `mp_int` to a small single digit value. Step number 1 ensures that the integer is reset to the default state. The single digit is set (*modulo* β) and the **used** count is adjusted accordingly.

```
File: bn_mp_set.c
016
017  /* set to a digit */
018  void mp_set (mp_int * a, mp_digit b)
019  {
020      mp_zero (a);
021      a->dp[0] = b & MP_MASK;
022      a->used = (a->dp[0] != 0) ? 1 : 0;
023  }
```

Line 20 calls `mp_zero()` to clear the `mp_int` and reset the sign. Line 21 copies the digit into the least significant location. Note the usage of a new constant **MP_MASK**. This constant is used to quickly reduce an integer modulo β . Since β is of the form 2^k for any suitable k it suffices to perform a binary AND with $MP_MASK = 2^k - 1$ to perform the reduction. Finally line 22 will set the **used** member with respect to the digit actually set. This function will always make the integer positive.

One important limitation of this function is that it will only set one digit. The size of a digit is not fixed, meaning source that uses this function should

take that into account. Only trivially small constants can be set using this function.

3.5.2 Setting Large Constants

To overcome the limitations of the `mp_set` algorithm the `mp_set_int` algorithm is ideal. It accepts a “long” data type as input and will always treat it as a 32-bit integer.

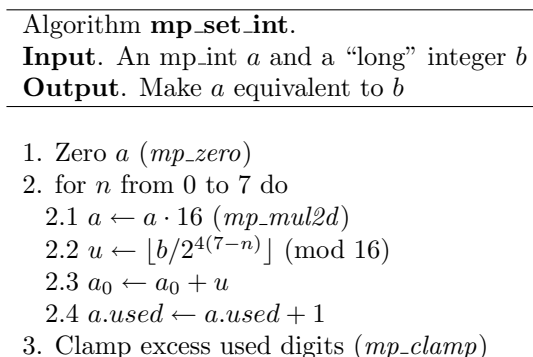


Figure 3.7: Algorithm `mp_set_int`

Algorithm `mp_set_int`. The algorithm performs eight iterations of a simple loop where in each iteration four bits from the source are added to the `mp_int`. Step 2.1 will multiply the current result by sixteen making room for four more bits in the less significant positions. In step 2.2 the next four bits from the source are extracted and are added to the `mp_int`. The **used** digit count is incremented to reflect the addition. The **used** digit counter is incremented since if any of the leading digits were zero the `mp_int` would have zero digits used and the newly added four bits would be ignored.

Excess zero digits are trimmed in steps 2.1 and 3 by using higher level algorithms `mp_mul2d` and `mp_clamp`.

```
File: bn_mp_set_int.c
016
017  /* set a 32-bit const */
018  int mp_set_int (mp_int * a, unsigned long b)
019  {
```

```

020     int      x, res;
021
022     mp_zero (a);
023
024     /* set four bits at a time */
025     for (x = 0; x < 8; x++) {
026         /* shift the number up four bits */
027         if ((res = mp_mul_2d (a, 4, a)) != MP_OKAY) {
028             return res;
029         }
030
031         /* OR in the top four bits of the source */
032         a->dp[0] |= (b >> 28) & 15;
033
034         /* shift the source up to the next four bits */
035         b <<= 4;
036
037         /* ensure that digits are not clamped off */
038         a->used += 1;
039     }
040     mp_clamp (a);
041     return MP_OKAY;
042 }

```

This function sets four bits of the number at a time to handle all practical **DIGIT_BIT** sizes. The weird addition on line 38 ensures that the newly added in bits are added to the number of digits. While it may not seem obvious as to why the digit counter does not grow exceedingly large it is because of the shift on line 27 as well as the call to `mp_clamp()` on line 40. Both functions will clamp excess leading digits which keeps the number of used digits low.

3.6 Comparisons

3.6.1 Unsigned Comparisions

Comparing a multiple precision integer is performed with the exact same algorithm used to compare two decimal numbers. For example, to compare 1,234 to 1,264 the digits are extracted by their positions. That is we compare $1 \cdot 10^3 + 2 \cdot 10^2 + 3 \cdot 10^1 + 4 \cdot 10^0$ to $1 \cdot 10^3 + 2 \cdot 10^2 + 6 \cdot 10^1 + 4 \cdot 10^0$ by comparing single digits at a time starting with the highest magnitude positions.

If any leading digit of one integer is greater than a digit in the same position of another integer then obviously it must be greater.

The first comparison routine that will be developed is the unsigned magnitude compare which will perform a comparison based on the digits of two `mp_int` variables alone. It will ignore the sign of the two inputs. Such a function is useful when an absolute comparison is required or if the signs are known to agree in advance.

To facilitate working with the results of the comparison functions three constants are required.

Constant	Meaning
<code>MP_GT</code>	Greater Than
<code>MP_EQ</code>	Equal To
<code>MP_LT</code>	Less Than

Figure 3.8: Comparison Return Codes

Algorithm **mp_cmp_mag**.

Input. Two `mp_ints` a and b .

Output. Unsigned comparison results (a to the left of b).

1. If $a.used > b.used$ then return(MP_GT)
 2. If $a.used < b.used$ then return(MP_LT)
 3. for n from $a.used - 1$ to 0 do
 - 3.1 if $a_n > b_n$ then return(MP_GT)
 - 3.2 if $a_n < b_n$ then return(MP_LT)
 4. Return(MP_EQ)
-

Figure 3.9: Algorithm `mp_cmp_mag`

Algorithm `mp_cmp_mag`. By saying “ a to the left of b ” it is meant that the comparison is with respect to a , that is if a is greater than b it will return `MP_GT` and similar with respect to when $a = b$ and $a < b$. The first two steps compare the number of digits used in both a and b . Obviously if the digit counts differ there would be an imaginary zero digit in the smaller number where the leading digit of the larger number is. If both have the same number

of digits than the actual digits themselves must be compared starting at the leading digit.

By step three both inputs must have the same number of digits so its safe to start from either $a.used - 1$ or $b.used - 1$ and count down to the zero'th digit. If after all of the digits have been compared, no difference is found, the algorithm returns **MP_EQ**.

File: bn_mp_cmp_mag.c

```

016
017  /* compare maginitude of two ints (unsigned) */
018  int mp_cmp_mag (mp_int * a, mp_int * b)
019  {
020      int      n;
021      mp_digit *tmpa, *tmpb;
022
023      /* compare based on # of non-zero digits */
024      if (a->used > b->used) {
025          return MP_GT;
026      }
027
028      if (a->used < b->used) {
029          return MP_LT;
030      }
031
032      /* alias for a */
033      tmpa = a->dp + (a->used - 1);
034
035      /* alias for b */
036      tmpb = b->dp + (a->used - 1);
037
038      /* compare based on digits */
039      for (n = 0; n < a->used; ++n, --tmpa, --tmpb) {
040          if (*tmpa > *tmpb) {
041              return MP_GT;
042          }
043
044          if (*tmpa < *tmpb) {
045              return MP_LT;
046          }
047      }
048      return MP_EQ;
049  }
```


The two if statements on lines 24 and 28 compare the number of digits in the two inputs. These two are performed before all of the digits are compared since it is a very cheap test to perform and can potentially save considerable time. The implementation given is also not valid without those two statements. *b.alloc* may be smaller than *a.used*, meaning that undefined values will be read from *b* past the end of the array of digits.

3.6.2 Signed Comparisons

Comparing with sign considerations is also fairly critical in several routines (*division for example*). Based on an unsigned magnitude comparison a trivial signed comparison algorithm can be written.

Algorithm mp_cmp.
Input. Two mp_ints <i>a</i> and <i>b</i>
Output. Signed Comparison Results (<i>a</i> to the left of <i>b</i>)

1. if *a.sign* = *MP_NEG* and *b.sign* = *MP_ZPOS* then return(*MP_LT*)
2. if *a.sign* = *MP_ZPOS* and *b.sign* = *MP_NEG* then return(*MP_GT*)
3. if *a.sign* = *MP_NEG* then
 - 3.1 Return the unsigned comparison of *b* and *a* (*mp_cmp_mag*)
- 4 Otherwise
 - 4.1 Return the unsigned comparison of *a* and *b*

Figure 3.10: Algorithm mp_cmp

Algorithm mp_cmp. The first two steps compare the signs of the two inputs. If the signs do not agree then it can return right away with the appropriate comparison code. When the signs are equal the digits of the inputs must be compared to determine the correct result. In step three the unsigned comparison flips the order of the arguments since they are both negative. For instance, if $-a > -b$ then $|a| < |b|$. Step number four will compare the two when they are both positive.

```
File: bn_mp_cmp.c
016
017  /* compare two ints (signed)*/
018  int
019  mp_cmp (mp_int * a, mp_int * b)
```

```

020  {
021  /* compare based on sign */
022  if (a->sign != b->sign) {
023      if (a->sign == MP_NEG) {
024          return MP_LT;
025      } else {
026          return MP_GT;
027      }
028  }
029
030  /* compare digits */
031  if (a->sign == MP_NEG) {
032      /* if negative compare opposite direction */
033      return mp_cmp_mag(b, a);
034  } else {
035      return mp_cmp_mag(a, b);
036  }
037  }

```

The two if statements on lines 22 and 23 perform the initial sign comparison. If the signs are not the equal then which ever has the positive sign is larger. At line 31, the inputs are compared based on magnitudes. If the signs were both negative then the unsigned comparison is performed in the opposite direction (*line 33*). Otherwise, the signs are assumed to be both positive and a forward direction unsigned comparison is performed.

Exercises

- [2] Modify algorithm `mp_set_int` to accept as input a variable length array of bits.
- [3] Give the probability that algorithm `mp_cmp_mag` will have to compare k digits of two random digits (of equal magnitude) before a difference is found.
- [1] Suggest a simple method to speed up the implementation of `mp_cmp_mag` based on the observations made in the previous problem.

Chapter 4

Basic Arithmetic

4.1 Introduction

At this point algorithms for initialization, clearing, zeroing, copying, comparing and setting small constants have been established. The next logical set of algorithms to develop are addition, subtraction and digit shifting algorithms. These algorithms make use of the lower level algorithms and are the crucial building block for the multiplication algorithms. It is very important that these algorithms are highly optimized. On their own they are simple $O(n)$ algorithms but they can be called from higher level algorithms which easily places them at $O(n^2)$ or even $O(n^3)$ work levels.

All of the algorithms within this chapter make use of the logical bit shift operations denoted by \ll and \gg for left and right logical shifts respectively. A logical shift is analogous to sliding the decimal point of radix-10 representations. For example, the real number 0.9345 is equivalent to 93.45% which is found by sliding the the decimal two places to the right (*multiplying by $\beta^2 = 10^2$*). Algebraically a binary logical shift is equivalent to a division or multiplication by a power of two. For example, $a \ll k = a \cdot 2^k$ while $a \gg k = \lfloor a/2^k \rfloor$.

One significant difference between a logical shift and the way decimals are shifted is that digits below the zero'th position are removed from the number. For example, consider $1101_2 \gg 1$ using decimal notation this would produce 110.1_2 . However, with a logical shift the result is 110_2 .

4.2 Addition and Subtraction

In common twos complement fixed precision arithmetic negative numbers are easily represented by subtraction from the modulus. For example, with 32-bit integers $a - b \pmod{2^{32}}$ is the same as $a + (2^{32} - b) \pmod{2^{32}}$ since $2^{32} \equiv 0 \pmod{2^{32}}$. As a result subtraction can be performed with a trivial series of logical operations and an addition.

However, in multiple precision arithmetic negative numbers are not represented in the same way. Instead a sign flag is used to keep track of the sign of the integer. As a result signed addition and subtraction are actually implemented as conditional usage of lower level addition or subtraction algorithms with the sign fixed up appropriately.

The lower level algorithms will add or subtract integers without regard to the sign flag. That is they will add or subtract the magnitude of the integers respectively.

4.2.1 Low Level Addition

An unsigned addition of multiple precision integers is performed with the same long-hand algorithm used to add decimal numbers. That is to add the trailing digits first and propagate the resulting carry upwards. Since this is a lower level algorithm the name will have a “s_” prefix. Historically that convention stems from the MPI library where “s_” stood for static functions that were hidden from the developer entirely.

Algorithm **s_mp_add**.

Input. Two mp_ints a and b

Output. The unsigned addition $c = |a| + |b|$.

1. if $a.used > b.used$ then
 - 1.1 $min \leftarrow b.used$
 - 1.2 $max \leftarrow a.used$
 - 1.3 $x \leftarrow a$
 2. else
 - 2.1 $min \leftarrow a.used$
 - 2.2 $max \leftarrow b.used$
 - 2.3 $x \leftarrow b$
 3. If $c.alloc < max + 1$ then grow c to hold at least $max + 1$ digits (*mp_grow*)
 4. $oldused \leftarrow c.used$
 5. $c.used \leftarrow max + 1$
 6. $u \leftarrow 0$
 7. for n from 0 to $min - 1$ do
 - 7.1 $c_n \leftarrow a_n + b_n + u$
 - 7.2 $u \leftarrow c_n >> lg(\beta)$
 - 7.3 $c_n \leftarrow c_n \pmod{\beta}$
 8. if $min \neq max$ then do
 - 8.1 for n from min to $max - 1$ do
 - 8.1.1 $c_n \leftarrow x_n + u$
 - 8.1.2 $u \leftarrow c_n >> lg(\beta)$
 - 8.1.3 $c_n \leftarrow c_n \pmod{\beta}$
 9. $c_{max} \leftarrow u$
 10. if $olduse > max$ then
 - 10.1 for n from $max + 1$ to $oldused - 1$ do
 - 10.1.1 $c_n \leftarrow 0$
 11. Clamp excess digits in c . (*mp_clamp*)
 12. Return(*MP_OKAY*)
-

Figure 4.1: Algorithm s_mp_add

Algorithm s_mp_add. This algorithm is loosely based on algorithm 14.7 of HAC [2, pp. 594] but has been extended to allow the inputs to have different magnitudes. Coincidentally the description of algorithm A in Knuth [1, pp. 266] shares the same deficiency as the algorithm from [2]. Even the MIX pseudo machine code presented by Knuth [1, pp. 266-267] is incapable of handling inputs which are of different magnitudes.

The first thing that has to be accomplished is to sort out which of the two

inputs is the largest. The addition logic will simply add all of the smallest input to the largest input and store that first part of the result in the destination. Then it will apply a simpler addition loop to excess digits of the larger input.

The first two steps will handle sorting the inputs such that min and max hold the digit counts of the two inputs. The variable x will be an `mp_int` alias for the largest input or the second input b if they have the same number of digits. After the inputs are sorted the destination c is grown as required to accomodate the sum of the two inputs. The original `used` count of c is copied and set to the new used count.

At this point the first addition loop will go through as many digit positions that both inputs have. The carry variable μ is set to zero outside the loop. Inside the loop an “addition” step requires three statements to produce one digit of the summand. First two digits from a and b are added together along with the carry μ . The carry of this step is extracted and stored in μ and finally the digit of the result c_n is truncated within the range $0 \leq c_n < \beta$.

Now all of the digit positions that both inputs have in common have been exhausted. If $min \neq max$ then x is an alias for one of the inputs that has more digits. A simplified addition loop is then used to essentially copy the remaining digits and the carry to the destination.

The final carry is stored in c_{max} and digits above max upto $oldused$ are zeroed which completes the addition.

File: `bn_s_mp_add.c`

```

016
017  /* low level addition, based on HAC pp.594, Algorithm 14.7 */
018  int
019  s_mp_add (mp_int * a, mp_int * b, mp_int * c)
020  {
021      mp_int *x;
022      int      olduse, res, min, max;
023
024      /* find sizes, we let |a| <= |b| which means we have to sort
025       * them. "x" will point to the input with the most digits
026       */
027      if (a->used > b->used) {
028          min = b->used;
029          max = a->used;
030          x = a;
031      } else {
032          min = a->used;
033          max = b->used;

```

```
034     x = b;
035 }
036
037 /* init result */
038 if (c->alloc < max + 1) {
039     if ((res = mp_grow (c, max + 1)) != MP_OKAY) {
040         return res;
041     }
042 }
043
044 /* get old used digit count and set new one */
045 olduse = c->used;
046 c->used = max + 1;
047
048 {
049     register mp_digit u, *tmpa, *tmpb, *tmpc;
050     register int i;
051
052     /* alias for digit pointers */
053
054     /* first input */
055     tmpa = a->dp;
056
057     /* second input */
058     tmpb = b->dp;
059
060     /* destination */
061     tmpc = c->dp;
062
063     /* zero the carry */
064     u = 0;
065     for (i = 0; i < min; i++) {
066         /* Compute the sum at one digit, T[i] = A[i] + B[i] + U */
067         *tmpc = *tmpa++ + *tmpb++ + u;
068
069         /* U = carry bit of T[i] */
070         u = *tmpc >> ((mp_digit)DIGIT_BIT);
071
072         /* take away carry bit from T[i] */
073         *tmpc++ &= MP_MASK;
074     }
075 }
```

```

076     /* now copy higher words if any, that is in A+B
077     * if A or B has more digits add those in
078     */
079     if (min != max) {
080         for (; i < max; i++) {
081             /* T[i] = X[i] + U */
082             *tmpc = x->dp[i] + u;
083
084             /* U = carry bit of T[i] */
085             u = *tmpc >> ((mp_digit)DIGIT_BIT);
086
087             /* take away carry bit from T[i] */
088             *tmpc++ &= MP_MASK;
089         }
090     }
091
092     /* add carry */
093     *tmpc++ = u;
094
095     /* clear digits above oldused */
096     for (i = c->used; i < oldused; i++) {
097         *tmpc++ = 0;
098     }
099 }
100
101 mp_clamp (c);
102 return MP_OKAY;
103 }

```

Lines 27 to 35 perform the initial sorting of the inputs and determine the *min* and *max* variables. Note that *x* is a pointer to a *mp_int* assigned to the largest input, in effect it is a local alias. Lines 37 to 42 ensure that the destination is grown to accommodate the result of the addition.

Similar to the implementation of *mp_copy* this function uses the braced code and local aliases coding style. The three aliases that are on lines 55, 58 and 61 represent the two inputs and destination variables respectively. These aliases are used to ensure the compiler does not have to dereference *a*, *b* or *c* (respectively) to access the digits of the respective *mp_int*.

The initial carry *u* is cleared on line 64, note that *u* is of type *mp_digit* which ensures type compatibility within the implementation. The initial addition loop begins on line 65 and ends on line 74. Similarly the conditional addition loop

begins on line 80 and ends on line 90. The addition is finished with the final carry being stored in *tmpc* on line 93. Note the “++” operator on the same line. After line 93 *tmpc* will point to the *c.used*’th digit of the mp_int *c*. This is useful for the next loop on lines 96 to 99 which set any old upper digits to zero.

4.2.2 Low Level Subtraction

The low level unsigned subtraction algorithm is very similar to the low level unsigned addition algorithm. The principle difference is that the unsigned subtraction algorithm requires the result to be positive. That is when computing $a - b$ the condition $|a| \geq |b|$ must be met for this algorithm to function properly. Keep in mind this low level algorithm is not meant to be used in higher level algorithms directly. This algorithm as will be shown can be used to create functional signed addition and subtraction algorithms.

For this algorithm a new variable is required to make the description simpler. Recall from section 1.3.1 that a mp_digit must be able to represent the range $0 \leq x < 2\beta$ for the algorithms to work correctly. However, it is allowable that a mp_digit represent a larger range of values. For this algorithm we will assume that the variable γ represents the number of bits available in a mp_digit (*this implies $2^\gamma > \beta$*).

For example, the default for LibTomMath is to use a “unsigned long” for the mp_digit “type” while $\beta = 2^{28}$. In ISO C an “unsigned long” data type must be able to represent $0 \leq x < 2^{32}$ meaning that in this case $\gamma = 32$.

Algorithm **s_mp_sub**.

Input. Two mp_ints a and b ($|a| \geq |b|$)

Output. The unsigned subtraction $c = |a| - |b|$.

1. $min \leftarrow b.used$
 2. $max \leftarrow a.used$
 3. If $c.alloc < max$ then grow c to hold at least max digits. (*mp_grow*)
 4. $oldused \leftarrow c.used$
 5. $c.used \leftarrow max$
 6. $u \leftarrow 0$
 7. for n from 0 to $min - 1$ do
 - 7.1 $c_n \leftarrow a_n - b_n - u$
 - 7.2 $u \leftarrow c_n \gg (\gamma - 1)$
 - 7.3 $c_n \leftarrow c_n \pmod{\beta}$
 8. if $min < max$ then do
 - 8.1 for n from min to $max - 1$ do
 - 8.1.1 $c_n \leftarrow a_n - u$
 - 8.1.2 $u \leftarrow c_n \gg (\gamma - 1)$
 - 8.1.3 $c_n \leftarrow c_n \pmod{\beta}$
 9. if $oldused > max$ then do
 - 9.1 for n from max to $oldused - 1$ do
 - 9.1.1 $c_n \leftarrow 0$
 10. Clamp excess digits of c . (*mp_clamp*).
 11. Return(*MP_OKAY*).
-

Figure 4.2: Algorithm s_mp_sub

Algorithm s_mp_sub. This algorithm performs the unsigned subtraction of two mp_int variables under the restriction that the result must be positive. That is when passing variables a and b the condition that $|a| \geq |b|$ must be met for the algorithm to function correctly. This algorithm is loosely based on algorithm 14.9 [2, pp. 595] and is similar to algorithm S in [1, pp. 267] as well. As was the case of the algorithm s_mp_add both other references lack discussion concerning various practical details such as when the inputs differ in magnitude.

The initial sorting of the inputs is trivial in this algorithm since a is guaranteed to have at least the same magnitude of b . Steps 1 and 2 set the min and max variables. Unlike the addition routine there is guaranteed to be no carry which means that the final result can be at most max digits in length as opposed to $max + 1$. Similar to the addition algorithm the **used** count of c is copied locally and set to the maximal count for the operation.

The subtraction loop that begins on step seven is essentially the same as the addition loop of algorithm `s_mp_add` except single precision subtraction is used instead. Note the use of the γ variable to extract the carry (*also known as the borrow*) within the subtraction loops. Under the assumption that two's complement single precision arithmetic is used this will successfully extract the desired carry.

For example, consider subtracting 0101_2 from 0100_2 where $\gamma = 4$ and $\beta = 2$. The least significant bit will force a carry upwards to the third bit which will be set to zero after the borrow. After the very first bit has been subtracted $4 - 1 \equiv 0011_2$ will remain, When the third bit of 0101_2 is subtracted from the result it will cause another carry. In this case though the carry will be forced to propagate all the way to the most significant bit.

Recall that $\beta < 2^\gamma$. This means that if a carry does occur just before the $lg(\beta)$ 'th bit it will propagate all the way to the most significant bit. Thus, the high order bits of the `mp_digit` that are not part of the actual digit will either be all zero, or all one. All that is needed is a single zero or one bit for the carry. Therefore a single logical shift right by $\gamma - 1$ positions is sufficient to extract the carry. This method of carry extraction may seem awkward but the reason for it becomes apparent when the implementation is discussed.

If b has a smaller magnitude than a then step 9 will force the carry and copy operation to propagate through the larger input a into c . Step 10 will ensure that any leading digits of c above the *max*'th position are zeroed.

File: `bn_s_mp_sub.c`

```

016
017  /* low level subtraction (assumes |a| > |b|), HAC pp.595 Algorithm 14.9 */
018  int
019  s_mp_sub (mp_int * a, mp_int * b, mp_int * c)
020  {
021      int      olduse, res, min, max;
022
023      /* find sizes */
024      min = b->used;
025      max = a->used;
026
027      /* init result */
028      if (c->alloc < max) {
029          if ((res = mp_grow (c, max)) != MP_OKAY) {
030              return res;
031          }
032      }

```

```
033     olduse = c->used;
034     c->used = max;
035
036     {
037     register mp_digit u, *tmpa, *tmpb, *tmpc;
038     register int i;
039
040     /* alias for digit pointers */
041     tmpa = a->dp;
042     tmpb = b->dp;
043     tmpc = c->dp;
044
045     /* set carry to zero */
046     u = 0;
047     for (i = 0; i < min; i++) {
048         /* T[i] = A[i] - B[i] - U */
049         *tmpc = *tmpa++ - *tmpb++ - u;
050
051         /* U = carry bit of T[i]
052          * Note this saves performing an AND operation since
053          * if a carry does occur it will propagate all the way to the
054          * MSB. As a result a single shift is enough to get the carry
055          */
056         u = *tmpc >> ((mp_digit)(CHAR_BIT * sizeof (mp_digit) - 1));
057
058         /* Clear carry from T[i] */
059         *tmpc++ &= MP_MASK;
060     }
061
062     /* now copy higher words if any, e.g. if A has more digits than B */
063     for (; i < max; i++) {
064         /* T[i] = A[i] - U */
065         *tmpc = *tmpa++ - u;
066
067         /* U = carry bit of T[i] */
068         u = *tmpc >> ((mp_digit)(CHAR_BIT * sizeof (mp_digit) - 1));
069
070         /* Clear carry from T[i] */
071         *tmpc++ &= MP_MASK;
072     }
073
074     /* clear digits above used (since we may not have grown result above) */
```

```

075     for (i = c->used; i < olduse; i++) {
076         *tmpc++ = 0;
077     }
078 }
079
080 mp_clamp (c);
081 return MP_OKAY;
082 }
083

```

Line 24 and 25 perform the initial hardcoded sorting of the inputs. In reality the *min* and *max* variables are only aliases and are only used to make the source code easier to read. Again the pointer alias optimization is used within this algorithm. Lines 41, 42 and 43 initialize the aliases for *a*, *b* and *c* respectively.

The first subtraction loop occurs on lines 46 through 60. The theory behind the subtraction loop is exactly the same as that for the addition loop. As remarked earlier there is an implementation reason for using the “awkward” method of extracting the carry (*see line 56*). The traditional method for extracting the carry would be to shift by $\lg(\beta)$ positions and logically AND the least significant bit. The AND operation is required because all of the bits above the $\lg(\beta)$ 'th bit will be set to one after a carry occurs from subtraction. This carry extraction requires two relatively cheap operations to extract the carry. The other method is to simply shift the most significant bit to the least significant bit thus extracting the carry with a single cheap operation. This optimization only works on twos compliment machines which is a safe assumption to make.

If *a* has a larger magnitude than *b* an additional loop (*see lines 63 through 72*) is required to propagate the carry through *a* and copy the result to *c*.

4.2.3 High Level Addition

Now that both lower level addition and subtraction algorithms have been established an effective high level signed addition algorithm can be established. This high level addition algorithm will be what other algorithms and developers will use to perform addition of *mp_int* data types.

Recall from section 5.2 that an *mp_int* represents an integer with an unsigned mantissa (*the array of digits*) and a **sign** flag. A high level addition is actually performed as a series of eight separate cases which can be optimized down to three unique cases.

Algorithm mp_add.
Input. Two mp_ints a and b
Output. The signed addition $c = a + b$.

1. if $a.sign = b.sign$ then do
 - 1.1 $c.sign \leftarrow a.sign$
 - 1.2 $c \leftarrow |a| + |b|$ (*s_mp_add*)
2. else do
 - 2.1 if $|a| < |b|$ then do (*mp_cmp_mag*)
 - 2.1.1 $c.sign \leftarrow b.sign$
 - 2.1.2 $c \leftarrow |b| - |a|$ (*s_mp_sub*)
 - 2.2 else do
 - 2.2.1 $c.sign \leftarrow a.sign$
 - 2.2.2 $c \leftarrow |a| - |b|$
3. Return(*MP_OKAY*).

Figure 4.3: Algorithm mp_add

Algorithm mp_add. This algorithm performs the signed addition of two mp_int variables. There is no reference algorithm to draw upon from either [1] or [2] since they both only provide unsigned operations. The algorithm is fairly straightforward but restricted since subtraction can only produce positive results.

Figure 4.4 lists all of the eight possible input combinations and is sorted to show that only three specific cases need to be handled. The return code of the unsigned operations at step 1.2, 2.1.2 and 2.2.2 are forwarded to step three to check for errors. This simplifies the description of the algorithm considerably and best follows how the implementation actually was achieved.

Also note how the **sign** is set before the unsigned addition or subtraction is performed. Recall from the descriptions of algorithms *s_mp_add* and *s_mp_sub* that the *mp_clamp* function is used at the end to trim excess digits. The *mp_clamp* algorithm will set the **sign** to **MP_ZPOS** when the **used** digit count reaches zero.

For example, consider performing $-a + a$ with algorithm *mp_add*. By the description of the algorithm the sign is set to **MP_NEG** which would produce a result of -0 . However, since the sign is set first then the unsigned addition is performed the subsequent usage of algorithm *mp_clamp* within algorithm

Sign of a	Sign of b	$ a > b $	Unsigned Operation	Result Sign Flag
+	+	Yes	$c = a + b$	$a.sign$
+	+	No	$c = a + b$	$a.sign$
-	-	Yes	$c = a + b$	$a.sign$
-	-	No	$c = a + b$	$a.sign$
+	-	No	$c = b - a$	$b.sign$
-	+	No	$c = b - a$	$b.sign$
+	-	Yes	$c = a - b$	$a.sign$
-	+	Yes	$c = a - b$	$a.sign$

Figure 4.4: Addition Guide Chart

s_mp_add will force -0 to become 0 .

File: bn_mp_add.c

```

016
017  /* high level addition (handles signs) */
018  int mp_add (mp_int * a, mp_int * b, mp_int * c)
019  {
020      int      sa, sb, res;
021
022      /* get sign of both inputs */
023      sa = a->sign;
024      sb = b->sign;
025
026      /* handle two cases, not four */
027      if (sa == sb) {
028          /* both positive or both negative */
029          /* add their magnitudes, copy the sign */
030          c->sign = sa;
031          res = s_mp_add (a, b, c);
032      } else {
033          /* one positive, the other negative */
034          /* subtract the one with the greater magnitude from */
035          /* the one of the lesser magnitude. The result gets */
036          /* the sign of the one with the greater magnitude. */
037          if (mp_cmp_mag (a, b) == MP_LT) {
038              c->sign = sb;
039              res = s_mp_sub (b, a, c);

```

```
040     } else {
041         c->sign = sa;
042         res = s_mp_sub (a, b, c);
043     }
044 }
045     return res;
046 }
047
```

The source code follows the algorithm fairly closely. The most notable new source code addition is the usage of the *res* integer variable which is used to pass result of the unsigned operations forward. Unlike in the algorithm, the variable *res* is merely returned as is without explicitly checking it and returning the constant `MP_OKAY`. The observation is this algorithm will succeed or fail only if the lower level functions do so. Returning their return code is sufficient.

4.2.4 High Level Subtraction

The high level signed subtraction algorithm is essentially the same as the high level signed addition algorithm.

Algorithm mp_sub.

Input. Two mp_ints a and b

Output. The signed subtraction $c = a - b$.

1. if $a.sign \neq b.sign$ then do
 - 1.1 $c.sign \leftarrow a.sign$
 - 1.2 $c \leftarrow |a| + |b|$ (*s_mp_add*)
 2. else do
 - 2.1 if $|a| \geq |b|$ then do (*mp_cmp_mag*)
 - 2.1.1 $c.sign \leftarrow a.sign$
 - 2.1.2 $c \leftarrow |a| - |b|$ (*s_mp_sub*)
 - 2.2 else do
 - 2.2.1 $c.sign \leftarrow \begin{cases} MP_ZPOS & \text{if } a.sign = MP_NEG \\ MP_NEG & \text{otherwise} \end{cases}$
 - 2.2.2 $c \leftarrow |b| - |a|$
 3. Return(*MP_OKAY*).
-

Figure 4.5: Algorithm mp_sub

Algorithm mp_sub. This algorithm performs the signed subtraction of two inputs. Similar to algorithm mp_add there is no reference in either [1] or [2]. Also this algorithm is restricted by algorithm s_mp_sub. Chart 4.6 lists the eight possible inputs and the operations required.

Sign of a	Sign of b	$ a \geq b $	Unsigned Operation	Result Sign Flag
+	-	Yes	$c = a + b$	$a.sign$
+	-	No	$c = a + b$	$a.sign$
-	+	Yes	$c = a + b$	$a.sign$
-	+	No	$c = a + b$	$a.sign$
+	+	Yes	$c = a - b$	$a.sign$
-	-	Yes	$c = a - b$	$a.sign$
+	+	No	$c = b - a$	opposite of $a.sign$
-	-	No	$c = b - a$	opposite of $a.sign$

Figure 4.6: Subtraction Guide Chart

Similar to the case of algorithm `mp_add` the **sign** is set first before the unsigned addition or subtraction. That is to prevent the algorithm from producing $-a - -a = -0$ as a result.

File: `bn_mp_sub.c`

```

016
017 /* high level subtraction (handles signs) */
018 int
019 mp_sub (mp_int * a, mp_int * b, mp_int * c)
020 {
021     int    sa, sb, res;
022
023     sa = a->sign;
024     sb = b->sign;
025
026     if (sa != sb) {
027         /* subtract a negative from a positive, OR */
028         /* subtract a positive from a negative. */
029         /* In either case, ADD their magnitudes, */
030         /* and use the sign of the first number. */
031         c->sign = sa;
032         res = s_mp_add (a, b, c);
033     } else {
034         /* subtract a positive from a positive, OR */
035         /* subtract a negative from a negative. */
036         /* First, take the difference between their */
037         /* magnitudes, then... */
038         if (mp_cmp_mag (a, b) != MP_LT) {
039             /* Copy the sign from the first */
040             c->sign = sa;
041             /* The first has a larger or equal magnitude */
042             res = s_mp_sub (a, b, c);
043         } else {
044             /* The result has the *opposite* sign from */
045             /* the first number. */
046             c->sign = (sa == MP_ZPOS) ? MP_NEG : MP_ZPOS;
047             /* The second has a larger magnitude */
048             res = s_mp_sub (b, a, c);
049         }
050     }
051     return res;
052 }
```

053

Much like the implementation of algorithm `mp_add` the variable `res` is used to catch the return code of the unsigned addition or subtraction operations and forward it to the end of the function. On line 38 the “not equal to” `MP_LT` expression is used to emulate a “greater than or equal to” comparison.

4.3 Bit and Digit Shifting

It is quite common to think of a multiple precision integer as a polynomial in x , that is $y = f(\beta)$ where $f(x) = \sum_{i=0}^{n-1} a_i x^i$. This notation arises within discussion of Montgomery and Diminished Radix Reduction as well as Karatsuba multiplication and squaring.

In order to facilitate operations on polynomials in x as above a series of simple “digit” algorithms have to be established. That is to shift the digits left or right as well to shift individual bits of the digits left and right. It is important to note that not all “shift” operations are on radix- β digits.

4.3.1 Multiplication by Two

In a binary system where the radix is a power of two multiplication by two not only arises often in other algorithms it is a fairly efficient operation to perform. A single precision logical shift left is sufficient to multiply a single digit by two.

Algorithm **mp_mul_2**.

Input. One mp_int a

Output. $b = 2a$.

1. If $b.alloc < a.used + 1$ then grow b to hold $a.used + 1$ digits. (*mp-grow*)
 2. $oldused \leftarrow b.used$
 3. $b.used \leftarrow a.used$
 4. $r \leftarrow 0$
 5. for n from 0 to $a.used - 1$ do
 - 5.1 $rr \leftarrow a_n \gg (lg(\beta) - 1)$
 - 5.2 $b_n \leftarrow (a_n \ll 1) + r \pmod{\beta}$
 - 5.3 $r \leftarrow rr$
 6. If $r \neq 0$ then do
 - 6.1 $b_{n+1} \leftarrow r$
 - 6.2 $b.used \leftarrow b.used + 1$
 7. If $b.used < oldused - 1$ then do
 - 7.1 for n from $b.used$ to $oldused - 1$ do
 - 7.1.1 $b_n \leftarrow 0$
 8. $b.sign \leftarrow a.sign$
 9. Return(*MP_OKAY*).
-

Figure 4.7: Algorithm mp_mul_2

Algorithm mp_mul_2. This algorithm will quickly multiply a mp_int by two provided β is a power of two. Neither [1] nor [2] describe such an algorithm despite the fact it arises often in other algorithms. The algorithm is setup much like the lower level algorithm s_mp_add since it is for all intents and purposes equivalent to the operation $b = |a| + |a|$.

Step 1 and 2 grow the input as required to accommodate the maximum number of **used** digits in the result. The initial **used** count is set to $a.used$ at step 4. Only if there is a final carry will the **used** count require adjustment.

Step 6 is an optimization implementation of the addition loop for this specific case. That is since the two values being added together are the same there is no need to perform two reads from the digits of a . Step 6.1 performs a single precision shift on the current digit a_n to obtain what will be the carry for the next iteration. Step 6.2 calculates the n 'th digit of the result as single precision shift of a_n plus the previous carry. Recall from section 4.1 that $a_n \ll 1$ is equivalent to $a_n \cdot 2$. An iteration of the addition loop is finished with forwarding the carry to the next iteration.

Step 7 takes care of any final carry by setting the $a.used$ 'th digit of the

result to the carry and augmenting the **used** count of *b*. Step 8 clears any leading digits of *b* in case it originally had a larger magnitude than *a*.

File: bn_mp_mul_2.c

```

016
017  /* b = a*2 */
018  int mp_mul_2(mp_int * a, mp_int * b)
019  {
020      int      x, res, oldused;
021
022      /* grow to accomodate result */
023      if (b->alloc < a->used + 1) {
024          if ((res = mp_grow (b, a->used + 1)) != MP_OKAY) {
025              return res;
026          }
027      }
028
029      oldused = b->used;
030      b->used = a->used;
031
032      {
033          register mp_digit r, rr, *tmpa, *tmpb;
034
035          /* alias for source */
036          tmpa = a->dp;
037
038          /* alias for dest */
039          tmpb = b->dp;
040
041          /* carry */
042          r = 0;
043          for (x = 0; x < a->used; x++) {
044
045              /* get what will be the *next* carry bit from the
046               * MSB of the current digit
047               */
048              rr = *tmpa >> ((mp_digit)(DIGIT_BIT - 1));
049
050              /* now shift up this digit, add in the carry [from the previous] */
051              *tmpb++ = ((*tmpa++ << ((mp_digit)1)) | r) & MP_MASK;
052
053              /* copy the carry that would be from the source
054               * digit into the next iteration

```

```
055     */
056     r = rr;
057 }
058
059 /* new leading digit? */
060 if (r != 0) {
061     /* add a MSB which is always 1 at this point */
062     *tmpb = 1;
063     ++(b->used);
064 }
065
066 /* now zero any excess digits on the destination
067  * that we didn't write to
068  */
069 tmpb = b->dp + b->used;
070 for (x = b->used; x < oldused; x++) {
071     *tmpb++ = 0;
072 }
073 }
074 b->sign = a->sign;
075 return MP_OKAY;
076 }
```

This implementation is essentially an optimized implementation of `s_mp_add` for the case of doubling an input. The only noteworthy difference is the use of the logical shift operator on line 51 to perform a single precision doubling.

4.3.2 Division by Two

A division by two can just as easily be accomplished with a logical shift right as multiplication by two can be with a logical shift left.

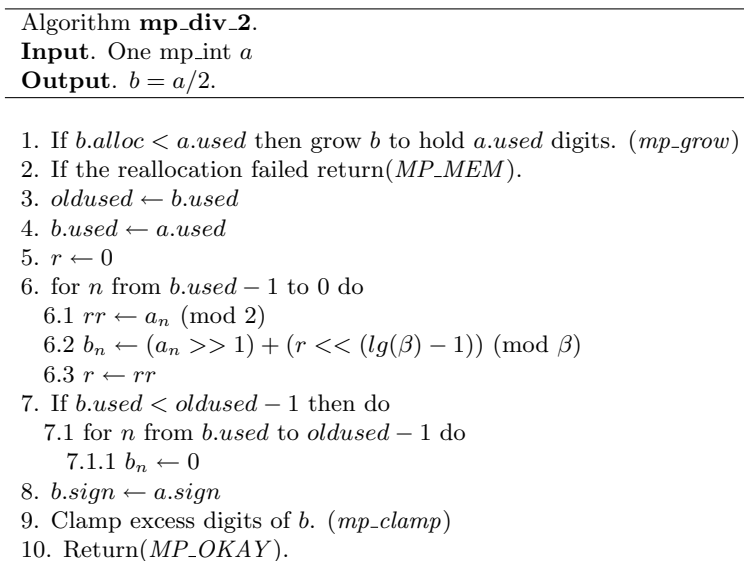


Figure 4.8: Algorithm mp_div_2

Algorithm mp_div_2. This algorithm will divide an mp_int by two using logical shifts to the right. Like mp_mul_2 it uses a modified low level addition core as the basis of the algorithm. Unlike mp_mul_2 the shift operations work from the leading digit to the trailing digit. The algorithm could be written to work from the trailing digit to the leading digit however, it would have to stop one short of $a.used - 1$ digits to prevent reading past the end of the array of digits.

Essentially the loop at step 6 is similar to that of mp_mul_2 except the logical shifts go in the opposite direction and the carry is at the least significant bit not the most significant bit.

```

File: bn_mp_div_2.c
016
017  /* b = a/2 */
018  int mp_div_2(mp_int * a, mp_int * b)
019  {
020      int      x, res, oldused;
021
022      /* copy */

```

```
023     if (b->alloc < a->used) {
024         if ((res = mp_grow (b, a->used)) != MP_OKAY) {
025             return res;
026         }
027     }
028
029     oldused = b->used;
030     b->used = a->used;
031     {
032         register mp_digit r, rr, *tmpa, *tmpb;
033
034         /* source alias */
035         tmpa = a->dp + b->used - 1;
036
037         /* dest alias */
038         tmpb = b->dp + b->used - 1;
039
040         /* carry */
041         r = 0;
042         for (x = b->used - 1; x >= 0; x--) {
043             /* get the carry for the next iteration */
044             rr = *tmpa & 1;
045
046             /* shift the current digit, add in carry and store */
047             *tmpb-- = (*tmpa-- >> 1) | (r << (DIGIT_BIT - 1));
048
049             /* forward carry to next iteration */
050             r = rr;
051         }
052
053         /* zero excess digits */
054         tmpb = b->dp + b->used;
055         for (x = b->used; x < oldused; x++) {
056             *tmpb++ = 0;
057         }
058     }
059     b->sign = a->sign;
060     mp_clamp (b);
061     return MP_OKAY;
062 }
```


4.4 Polynomial Basis Operations

Recall from section 4.3 that any integer can be represented as a polynomial in x as $y = f(\beta)$. Such a representation is also known as the polynomial basis [3, pp. 48]. Given such a notation a multiplication or division by x amounts to shifting whole digits a single place. The need for such operations arises in several other higher level algorithms such as Barrett and Montgomery reduction, integer division and Karatsuba multiplication.

Converting from an array of digits to polynomial basis is very simple. Consider the integer $y \equiv (a_2, a_1, a_0)_\beta$ and recall that $y = \sum_{i=0}^2 a_i \beta^i$. Simply replace β with x and the expression is in polynomial basis. For example, $f(x) = 8x + 9$ is the polynomial basis representation for 89 using radix ten. That is, $f(10) = 8(10) + 9 = 89$.

4.4.1 Multiplication by x

Given a polynomial in x such as $f(x) = a_n x^n + a_{n-1} x^{n-1} + \dots + a_0$ multiplying by x amounts to shifting the coefficients up one degree. In this case $f(x) \cdot x = a_n x^{n+1} + a_{n-1} x^n + \dots + a_0 x$. From a scalar basis point of view multiplying by x is equivalent to multiplying by the integer β .

Algorithm **mp_lshd**.

Input. One mp_int a and an integer b

Output. $a \leftarrow a \cdot \beta^b$ (equivalent to multiplication by x^b).

1. If $b \leq 0$ then return(MP_OKAY).
 2. If $a.alloc < a.used + b$ then grow a to at least $a.used + b$ digits. (mp_grow).
 3. If the reallocation failed return(MP_MEM).
 4. $a.used \leftarrow a.used + b$
 5. $i \leftarrow a.used - 1$
 6. $j \leftarrow a.used - 1 - b$
 7. for n from $a.used - 1$ to b do
 - 7.1 $a_i \leftarrow a_j$
 - 7.2 $i \leftarrow i - 1$
 - 7.3 $j \leftarrow j - 1$
 8. for n from 0 to $b - 1$ do
 - 8.1 $a_n \leftarrow 0$
 9. Return(MP_OKAY).
-

Figure 4.9: Algorithm mp_lshd

Algorithm mp_lshd. This algorithm multiplies an mp_int by the b 'th power of x . This is equivalent to multiplying by β^b . The algorithm differs from the other algorithms presented so far as it performs the operation in place instead storing the result in a separate location. The motivation behind this change is due to the way this function is typically used. Algorithms such as mp_add store the result in an optionally different third mp_int because the original inputs are often still required. Algorithm mp_lshd (*and similarly algorithm mp_rshd*) is typically used on values where the original value is no longer required. The algorithm will return success immediately if $b \leq 0$ since the rest of algorithm is only valid when $b > 0$.

First the destination a is grown as required to accomodate the result. The counters i and j are used to form a *sliding window* over the digits of a of length b . The head of the sliding window is at i (*the leading digit*) and the tail at j (*the trailing digit*). The loop on step 7 copies the digit from the tail to the head. In each iteration the window is moved down one digit. The last loop on step 8 sets the lower b digits to zero.

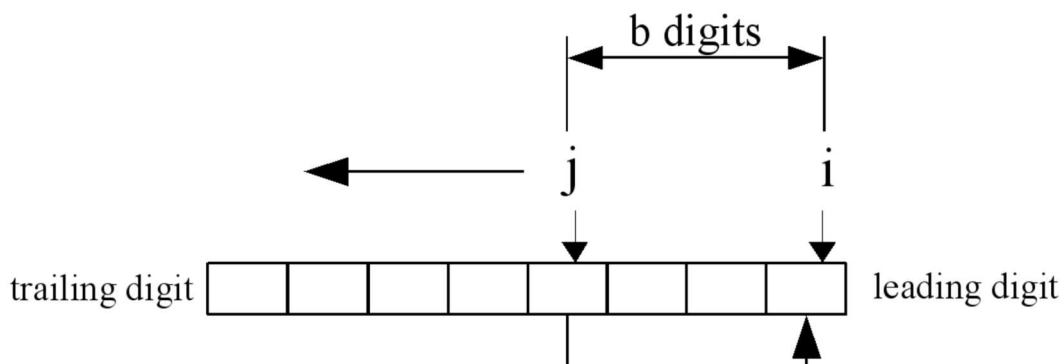


Figure 4.10: Sliding Window Movement

File: bn_mp_lshd.c

```

016
017 /* shift left a certain amount of digits */
018 int mp_lshd (mp_int * a, int b)
019 {
020     int    x, res;
021
022     /* if its less than zero return */
023     if (b <= 0) {
024         return MP_OKAY;
025     }
026
027     /* grow to fit the new digits */
028     if (a->alloc < a->used + b) {
029         if ((res = mp_grow (a, a->used + b)) != MP_OKAY) {
030             return res;
031         }
032     }
033
034     {
035         register mp_digit *top, *bottom;
036
037         /* increment the used by the shift amount then copy upwards */
038         a->used += b;

```

```

039
040     /* top */
041     top = a->dp + a->used - 1;
042
043     /* base */
044     bottom = a->dp + a->used - 1 - b;
045
046     /* much like mp_rshd this is implemented using a sliding window
047      * except the window goes the otherway around. Copying from
048      * the bottom to the top. see bn_mp_rshd.c for more info.
049      */
050     for (x = a->used - 1; x >= b; x--) {
051         *top-- = *bottom--;
052     }
053
054     /* zero the lower digits */
055     top = a->dp;
056     for (x = 0; x < b; x++) {
057         *top++ = 0;
058     }
059 }
060 return MP_OKAY;
061 }

```

The if statement on line 23 ensures that the b variable is greater than zero. The **used** count is incremented by b before the copy loop begins. This eliminates the need for an additional variable in the for loop. The variable *top* on line 41 is an alias for the leading digit while *bottom* on line 44 is an alias for the trailing edge. The aliases form a window of exactly b digits over the input.

4.4.2 Division by x

Division by powers of x is easily achieved by shifting the digits right and removing any that will end up to the right of the zero'th digit.

Algorithm **mp_rshd**.
Input. One mp_int a and an integer b
Output. $a \leftarrow a/\beta^b$ (Divide by x^b).

1. If $b \leq 0$ then return.
2. If $a.\text{used} \leq b$ then do
 - 2.1 Zero a . (mp_zero).
 - 2.2 Return.
3. $i \leftarrow 0$
4. $j \leftarrow b$
5. for n from 0 to $a.\text{used} - b - 1$ do
 - 5.1 $a_i \leftarrow a_j$
 - 5.2 $i \leftarrow i + 1$
 - 5.3 $j \leftarrow j + 1$
6. for n from $a.\text{used} - b$ to $a.\text{used} - 1$ do
 - 6.1 $a_n \leftarrow 0$
7. $a.\text{used} \leftarrow a.\text{used} - b$
8. Return.

Figure 4.11: Algorithm mp_rshd

Algorithm mp_rshd. This algorithm divides the input in place by the b 'th power of x . It is analogous to dividing by a β^b but much quicker since it does not require single precision division. This algorithm does not actually return an error code as it cannot fail.

If the input b is less than one the algorithm quickly returns without performing any work. If the **used** count is less than or equal to the shift count b then it will simply zero the input and return.

After the trivial cases of inputs have been handled the sliding window is setup. Much like the case of algorithm mp_lshd a sliding window that is b digits wide is used to copy the digits. Unlike mp_lshd the window slides in the opposite direction from the trailing to the leading digit. Also the digits are copied from the leading to the trailing edge.

Once the window copy is complete the upper digits must be zeroed and the **used** count decremented.

File: bn_mp_rshd.c

```
016
017  /* shift right a certain amount of digits */
018  void mp_rshd (mp_int * a, int b)
```

```

019  {
020      int      x;
021
022      /* if b <= 0 then ignore it */
023      if (b <= 0) {
024          return;
025      }
026
027      /* if b > used then simply zero it and return */
028      if (a->used <= b) {
029          mp_zero (a);
030          return;
031      }
032
033      {
034          register mp_digit *bottom, *top;
035
036          /* shift the digits down */
037
038          /* bottom */
039          bottom = a->dp;
040
041          /* top [offset into digits] */
042          top = a->dp + b;
043
044          /* this is implemented as a sliding window where
045           * the window is b-digits long and digits from
046           * the top of the window are copied to the bottom
047           *
048           * e.g.
049
050           b-2 | b-1 | b0 | b1 | b2 | ... | bb | ---->
051                /\                | ---->
052                \-----/ ---->
053           */
054          for (x = 0; x < (a->used - b); x++) {
055              *bottom++ = *top++;
056          }
057
058          /* zero the top digits */
059          for (; x < a->used; x++) {
060              *bottom++ = 0;

```

```
061     }
062   }
063
064   /* remove excess digits */
065   a->used -= b;
066 }
```

The only noteworthy element of this routine is the lack of a return type.
– Will update later to give it a return type...Tom

4.5 Powers of Two

Now that algorithms for moving single bits as well as whole digits exist algorithms for moving the “in between” distances are required. For example, to quickly multiply by 2^k for any k without using a full multiplier algorithm would prove useful. Instead of performing single shifts k times to achieve a multiplication by $2^{\pm k}$ a mixture of whole digit shifting and partial digit shifting is employed.

4.5.1 Multiplication by Power of Two

Algorithm **mp_mul_2d**.
Input. One mp_int a and an integer b
Output. $c \leftarrow a \cdot 2^b$.

1. $c \leftarrow a$. (*mp_copy*)
2. If $c.alloc < c.used + \lfloor b/lg(\beta) \rfloor + 2$ then grow c accordingly.
3. If the reallocation failed return(*MP_MEM*).
4. If $b \geq lg(\beta)$ then
 - 4.1 $c \leftarrow c \cdot \beta^{\lfloor b/lg(\beta) \rfloor}$ (*mp_lshd*).
 - 4.2 If step 4.1 failed return(*MP_MEM*).
5. $d \leftarrow b \pmod{lg(\beta)}$
6. If $d \neq 0$ then do
 - 6.1 $mask \leftarrow 2^d$
 - 6.2 $r \leftarrow 0$
 - 6.3 for n from 0 to $c.used - 1$ do
 - 6.3.1 $rr \leftarrow c_n \gg (lg(\beta) - d) \pmod{mask}$
 - 6.3.2 $c_n \leftarrow (c_n \ll d) + r \pmod{\beta}$
 - 6.3.3 $r \leftarrow rr$
 - 6.4 If $r > 0$ then do
 - 6.4.1 $c_{c.used} \leftarrow r$
 - 6.4.2 $c.used \leftarrow c.used + 1$
7. Return(*MP_OKAY*).

Figure 4.12: Algorithm mp_mul_2d

Algorithm mp_mul_2d. This algorithm multiplies a by 2^b and stores the result in c . The algorithm uses algorithm *mp_lshd* and a derivative of algorithm *mp_mul_2* to quickly compute the product.

First the algorithm will multiply a by $x^{\lfloor b/lg(\beta) \rfloor}$ which will ensure that the remainder multiplicand is less than β . For example, if $b = 37$ and $\beta = 2^{28}$ then this step will multiply by x leaving a multiplication by $2^{37-28} = 2^9$ left.

After the digits have been shifted appropriately at most $lg(\beta) - 1$ shifts are left to perform. Step 5 calculates the number of remaining shifts required. If it is non-zero a modified shift loop is used to calculate the remaining product. Essentially the loop is a generic version of algorithm *mp_mul2* designed to handle any shift count in the range $1 \leq x < lg(\beta)$. The *mask* variable is used to extract the upper d bits to form the carry for the next iteration.

This algorithm is loosely measured as a $O(2n)$ algorithm which means that if the input is n -digits that it takes $2n$ “time” to complete. It is possible to optimize this algorithm down to a $O(n)$ algorithm at a cost of making the

algorithm slightly harder to follow.

```

File: bn_mp_mul_2d.c
016
017  /* shift left by a certain bit count */
018  int mp_mul_2d (mp_int * a, int b, mp_int * c)
019  {
020      mp_digit d;
021      int      res;
022
023      /* copy */
024      if (a != c) {
025          if ((res = mp_copy (a, c)) != MP_OKAY) {
026              return res;
027          }
028      }
029
030      if (c->alloc < (int)(c->used + b/DIGIT_BIT + 1)) {
031          if ((res = mp_grow (c, c->used + b / DIGIT_BIT + 1)) != MP_OKAY) {
032              return res;
033          }
034      }
035
036      /* shift by as many digits in the bit count */
037      if (b >= (int)DIGIT_BIT) {
038          if ((res = mp_lshd (c, b / DIGIT_BIT)) != MP_OKAY) {
039              return res;
040          }
041      }
042
043      /* shift any bit count < DIGIT_BIT */
044      d = (mp_digit) (b % DIGIT_BIT);
045      if (d != 0) {
046          register mp_digit *tmpc, shift, mask, r, rr;
047          register int x;
048
049          /* bitmask for carries */
050          mask = (((mp_digit)1) << d) - 1;
051
052          /* shift for msbs */
053          shift = DIGIT_BIT - d;
054
055          /* alias */

```

```
056     tmpc = c->dp;
057
058     /* carry */
059     r     = 0;
060     for (x = 0; x < c->used; x++) {
061         /* get the higher bits of the current word */
062         rr = (*tmpc >> shift) & mask;
063
064         /* shift the current word and OR in the carry */
065         *tmpc = ((*tmpc << d) | r) & MP_MASK;
066         ++tmpc;
067
068         /* set the carry to the carry bits of the current word */
069         r = rr;
070     }
071
072     /* set final carry */
073     if (r != 0) {
074         c->dp[(c->used)++] = r;
075     }
076 }
077 mp_clamp (c);
078 return MP_OKAY;
079 }
```

Notes to be revised when code is updated. – Tom

4.5.2 Division by Power of Two

Algorithm **mp_div_2d**.

Input. One mp_int a and an integer b

Output. $c \leftarrow \lfloor a/2^b \rfloor, d \leftarrow a \pmod{2^b}$.

1. If $b \leq 0$ then do
 - 1.1 $c \leftarrow a$ (*mp_copy*)
 - 1.2 $d \leftarrow 0$ (*mp_zero*)
 - 1.3 Return(*MP_OKAY*).
 2. $c \leftarrow a$
 3. $d \leftarrow a \pmod{2^b}$ (*mp_mod_2d*)
 4. If $b \geq \lg(\beta)$ then do
 - 4.1 $c \leftarrow \lfloor c/\beta^{\lfloor b/\lg(\beta) \rfloor} \rfloor$ (*mp_rshd*).
 5. $k \leftarrow b \pmod{\lg(\beta)}$
 6. If $k \neq 0$ then do
 - 6.1 $mask \leftarrow 2^k$
 - 6.2 $r \leftarrow 0$
 - 6.3 for n from $c.used - 1$ to 0 do
 - 6.3.1 $rr \leftarrow c_n \pmod{mask}$
 - 6.3.2 $c_n \leftarrow (c_n \gg k) + (r \ll (\lg(\beta) - k))$
 - 6.3.3 $r \leftarrow rr$
 7. Clamp excess digits of c . (*mp_clamp*)
 8. Return(*MP_OKAY*).
-

Figure 4.13: Algorithm mp_div_2d

Algorithm mp_div_2d. This algorithm will divide an input a by 2^b and produce the quotient and remainder. The algorithm is designed much like algorithm mp_mul_2d by first using whole digit shifts then single precision shifts. This algorithm will also produce the remainder of the division by using algorithm mp_mod_2d.

File: bn_mp_div_2d.c

```

016
017  /* shift right by a certain bit count (store quotient in c, optional remaind
    er in d) */
018  int mp_div_2d (mp_int * a, int b, mp_int * c, mp_int * d)
019  {
020      mp_digit D, r, rr;
021      int      x, res;
022      mp_int  t;
023

```

```

024
025 /* if the shift count is <= 0 then we do no work */
026 if (b <= 0) {
027     res = mp_copy (a, c);
028     if (d != NULL) {
029         mp_zero (d);
030     }
031     return res;
032 }
033
034 if ((res = mp_init (&t)) != MP_OKAY) {
035     return res;
036 }
037
038 /* get the remainder */
039 if (d != NULL) {
040     if ((res = mp_mod_2d (a, b, &t)) != MP_OKAY) {
041         mp_clear (&t);
042         return res;
043     }
044 }
045
046 /* copy */
047 if ((res = mp_copy (a, c)) != MP_OKAY) {
048     mp_clear (&t);
049     return res;
050 }
051
052 /* shift by as many digits in the bit count */
053 if (b >= (int)DIGIT_BIT) {
054     mp_rshd (c, b / DIGIT_BIT);
055 }
056
057 /* shift any bit count < DIGIT_BIT */
058 D = (mp_digit) (b % DIGIT_BIT);
059 if (D != 0) {
060     register mp_digit *tmpc, mask, shift;
061
062     /* mask */
063     mask = (((mp_digit)1) << D) - 1;
064
065     /* shift for lsb */

```

```

066     shift = DIGIT_BIT - D;
067
068     /* alias */
069     tmpc = c->dp + (c->used - 1);
070
071     /* carry */
072     r = 0;
073     for (x = c->used - 1; x >= 0; x--) {
074         /* get the lower bits of this word in a temp */
075         rr = *tmpc & mask;
076
077         /* shift the current word and mix in the carry bits from the previous
word */
078         *tmpc = (*tmpc >> D) | (r << shift);
079         --tmpc;
080
081         /* set the carry to the carry bits of the current word found above */
082         r = rr;
083     }
084 }
085 mp_clamp (c);
086 if (d != NULL) {
087     mp_exch (&t, d);
088 }
089 mp_clear (&t);
090 return MP_OKAY;
091 }

```

The implementation of algorithm `mp_div_2d` is slightly different than the algorithm specifies. The remainder d may be optionally ignored by passing `NULL` as the pointer to the `mp_int` variable. The temporary `mp_int` variable t is used to hold the result of the remainder operation until the end. This allows d and a to represent the same `mp_int` without modifying a before the quotient is obtained.

The remainder of the source code is essentially the same as the source code for `mp_mul_2d`. (– Fix this paragraph up later, Tom).

4.5.3 Remainder of Division by Power of Two

The last algorithm in the series of polynomial basis power of two algorithms is calculating the remainder of division by 2^b . This algorithm benefits from

the fact that in twos complement arithmetic $a \pmod{2^b}$ is the same as a AND $2^b - 1$.

Algorithm **mp_mod_2d**.

Input. One mp_int a and an integer b

Output. $c \leftarrow a \pmod{2^b}$.

1. If $b \leq 0$ then do
 - 1.1 $c \leftarrow 0$ (*mp_zero*)
 - 1.2 Return(*MP_OKAY*).
 2. If $b > a.\text{used} \cdot \lg(\beta)$ then do
 - 2.1 $c \leftarrow a$ (*mp_copy*)
 - 2.2 Return the result of step 2.1.
 3. $c \leftarrow a$
 4. If step 3 failed return(*MP_MEM*).
 5. for n from $\lceil b/\lg(\beta) \rceil$ to $c.\text{used}$ do
 - 5.1 $c_n \leftarrow 0$
 6. $k \leftarrow b \pmod{\lg(\beta)}$
 7. $c_{\lfloor b/\lg(\beta) \rfloor} \leftarrow c_{\lfloor b/\lg(\beta) \rfloor} \pmod{2^k}$.
 8. Clamp excess digits of c . (*mp_clamp*)
 9. Return(*MP_OKAY*).
-

Figure 4.14: Algorithm mp_mod_2d

Algorithm mp_mod_2d. This algorithm will quickly calculate the value of $a \pmod{2^b}$. First if b is less than or equal to zero the result is set to zero. If b is greater than the number of bits in a then it simply copies a to c and returns. Otherwise, a is copied to b , leading digits are removed and the remaining leading digit is trimmed to the exact bit count.

```
File: bn_mp_mod_2d.c
016
017 /* calc a value mod 2**b */
018 int
019 mp_mod_2d (mp_int * a, int b, mp_int * c)
020 {
021     int    x, res;
022
023     /* if b is <= 0 then zero the int */
024     if (b <= 0) {
025         mp_zero (c);
```

```
026     return MP_OKAY;
027 }
028
029 /* if the modulus is larger than the value than return */
030 if (b > (int) (a->used * DIGIT_BIT)) {
031     res = mp_copy (a, c);
032     return res;
033 }
034
035 /* copy */
036 if ((res = mp_copy (a, c)) != MP_OKAY) {
037     return res;
038 }
039
040 /* zero digits above the last digit of the modulus */
041 for (x = (b / DIGIT_BIT) + ((b % DIGIT_BIT) == 0 ? 0 : 1); x < c->used; x+
+) {
042     c->dp[x] = 0;
043 }
044 /* clear the digit that is not completely outside/inside the modulus */
045 c->dp[b / DIGIT_BIT] &=
046     (mp_digit) (((mp_digit) 1) << (((mp_digit) b) % DIGIT_BIT)) - ((mp_digi
t) 1));
047 mp_clamp (c);
048 return MP_OKAY;
049 }
```

– Add comments later, Tom.

Exercises

- [3] Devise an algorithm that performs $a \cdot 2^b$ for generic values of b in $O(n)$ time.
- [3] Devise an efficient algorithm to multiply by small low hamming weight values such as 3, 5 and 9. Extend it to handle all values upto 64 with a hamming weight less than three.
- [2] Modify the preceding algorithm to handle values of the form $2^k - 1$ as well.
- [3] Using only algorithms `mp_mul_2`, `mp_div_2` and `mp_add` create an algorithm to multiply two integers in roughly $O(2n^2)$ time for any n -bit input. Note that the time of addition is ignored in the calculation.
- [5] Improve the previous algorithm to have a working time of at most $O\left(2^{(k-1)}n + \binom{2n^2}{k}\right)$ for an appropriate choice of k . Again ignore the cost of addition.
- [2] Devise a chart to find optimal values of k for the previous problem for $n = 64 \dots 1024$ in steps of 64.
- [2] Using only algorithms `mp_abs` and `mp_sub` devise another method for calculating the result of a signed comparison.

Chapter 5

Multiplication and Squaring

5.1 The Multipliers

For most number theoretic problems including certain public key cryptographic algorithms, the “multipliers” form the most important subset of algorithms of any multiple precision integer package. The set of multiplier algorithms include integer multiplication, squaring and modular reduction where in each of the algorithms single precision multiplication is the dominant operation performed. This chapter will discuss integer multiplication and squaring, leaving modular reductions for the subsequent chapter.

The importance of the multiplier algorithms is for the most part driven by the fact that certain popular public key algorithms are based on modular exponentiation, that is computing $d \equiv a^b \pmod{c}$ for some arbitrary choice of a , b , c and d . During a modular exponentiation the majority¹ of the processor time is spent performing single precision multiplications.

For centuries general purpose multiplication has required a lengthly $O(n^2)$ process, whereby each digit of one multiplicand has to be multiplied against every digit of the other multiplicand. Traditional long-hand multiplication is based on this process; while the techniques can differ the overall algorithm used is essentially the same. Only “recently” have faster algorithms been studied. First Karatsuba multiplication was discovered in 1962. This algorithm can

¹Roughly speaking a modular exponentiation will spend about 40% of the time performing modular reductions, 35% of the time performing squaring and 25% of the time performing multiplications.

multiply two numbers with considerably fewer single precision multiplications when compared to the long-hand approach. This technique led to the discovery of polynomial basis algorithms (*good reference?*) and subsequently Fourier Transform based solutions.

5.2 Multiplication

5.2.1 The Baseline Multiplication

Computing the product of two integers in software can be achieved using a trivial adaptation of the standard $O(n^2)$ long-hand multiplication algorithm that school children are taught. The algorithm is considered an $O(n^2)$ algorithm since for two n -digit inputs n^2 single precision multiplications are required. More specifically for a m and n digit input $m \cdot n$ single precision multiplications are required. To simplify most discussions, it will be assumed that the inputs have comparable number of digits.

The “baseline multiplication” algorithm is designed to act as the “catch-all” algorithm, only to be used when the faster algorithms cannot be used. This algorithm does not use any particularly interesting optimizations and should ideally be avoided if possible. One important facet of this algorithm, is that it has been modified to only produce a certain amount of output digits as resolution. The importance of this modification will become evident during the discussion of Barrett modular reduction. Recall that for a n and m digit input the product will be at most $n + m$ digits. Therefore, this algorithm can be reduced to a full multiplier by having it produce $n + m$ digits of the product.

Recall from sub-section 4.2.2 the definition of γ as the number of bits in the type **mp_digit**. We shall now extend the variable set to include α which shall represent the number of bits in the type **mp_word**. This implies that $2^\alpha > 2 \cdot \beta^2$. The constant $\delta = 2^{\alpha - 2lg(\beta)}$ will represent the maximal weight of any column in a product (*see sub-section 5.2.2 for more information*).

Algorithm **s_mp_mul_digs**.

Input. mp_int a , mp_int b and an integer $digs$

Output. $c \leftarrow |a| \cdot |b| \pmod{\beta^{digs}}$.

1. If $\min(a.used, b.used) < \delta$ then do
 - 1.1 Calculate $c = |a| \cdot |b|$ by the Comba method (*see algorithm 5.5*).
 - 1.2 Return the result of step 1.1

Allocate and initialize a temporary mp_int.

2. Init t to be of size $digs$
3. If step 2 failed return(MP_MEM).
4. $t.used \leftarrow digs$

Compute the product.

5. for ix from 0 to $a.used - 1$ do
 - 5.1 $u \leftarrow 0$
 - 5.2 $pb \leftarrow \min(b.used, digs - ix)$
 - 5.3 If $pb < 1$ then goto step 6.
 - 5.4 for iy from 0 to $pb - 1$ do
 - 5.4.1 $\hat{r} \leftarrow t_{iy+ix} + a_{ix} \cdot b_{iy} + u$
 - 5.4.2 $t_{iy+ix} \leftarrow \hat{r} \pmod{\beta}$
 - 5.4.3 $u \leftarrow \lfloor \hat{r} / \beta \rfloor$
 - 5.5 if $ix + pb < digs$ then do
 - 5.5.1 $t_{ix+pb} \leftarrow u$
 6. Clamp excess digits of t .
 7. Swap c with t
 8. Clear t
 9. Return(MP_OKAY).
-

Figure 5.1: Algorithm s_mp_mul_digs

Algorithm s_mp_mul_digs. This algorithm computes the unsigned product of two inputs a and b , limited to an output precision of $digs$ digits. While it may seem a bit awkward to modify the function from its simple $O(n^2)$ description, the usefulness of partial multipliers will arise in a subsequent algorithm. The algorithm is loosely based on algorithm 14.12 from [2, pp. 595] and is similar to Algorithm M of Knuth [1, pp. 268]. Algorithm s_mp_mul_digs differs from these cited references since it can produce a variable output precision regardless of the precision of the inputs.

The first thing this algorithm checks for is whether a Comba multiplier can

be used instead. If the minimum digit count of either input is less than δ , then the Comba method may be used instead. After the Comba method is ruled out, the baseline algorithm begins. A temporary `mp_int` variable t is used to hold the intermediate result of the product. This allows the algorithm to be used to compute products when either $a = c$ or $b = c$ without overwriting the inputs.

All of step 5 is the infamous $O(n^2)$ multiplication loop slightly modified to only produce upto $digs$ digits of output. The pb variable is given the count of digits to read from b inside the nested loop. If $pb \leq 1$ then no more output digits can be produced and the algorithm will exit the loop. The best way to think of the loops are as a series of $pb \times 1$ multiplications. That is, in each pass of the innermost loop a_{ix} is multiplied against b and the result is added (*with an appropriate shift*) to t .

For example, consider multiplying 576 by 241. That is equivalent to computing $10^0(1)(576) + 10^1(4)(576) + 10^2(2)(576)$ which is best visualized in the following table.

			5	7	6	
×			2	4	1	
			5	7	6	$10^0(1)(576)$
	2	3	6	1	6	$10^1(4)(576) + 10^0(1)(576)$
1	3	8	8	1	6	$10^2(2)(576) + 10^1(4)(576) + 10^0(1)(576)$

Figure 5.2: Long-Hand Multiplication Diagram

Each row of the product is added to the result after being shifted to the left (*multiplied by a power of the radix*) by the appropriate count. That is in pass ix of the inner loop the product is added starting at the ix 'th digit of the result.

Step 5.4.1 introduces the hat symbol (*e.g.* \hat{r}) which represents a double precision variable. The multiplication on that step is assumed to be a double wide output single precision multiplication. That is, two single precision variables are multiplied to produce a double precision result. The step is somewhat optimized from a long-hand multiplication algorithm because the carry from the addition in step 5.4.1 is propagated through the nested loop. If the carry was not propagated immediately it would overflow the single precision digit t_{ix+iy} and the result would be lost.

At step 5.5 the nested loop is finished and any carry that was left over should be forwarded. The carry does not have to be added to the $ix + pb$ 'th digit since

that digit is assumed to be zero at this point. However, if $ix + pb \geq digs$ the carry is not set as it would make the result exceed the precision requested.

File: bn_s_mp_mul_digs.c

```

016
017 /* multiplies |a| * |b| and only computes upto digs digits of result
018 * HAC pp. 595, Algorithm 14.12 Modified so you can control how
019 * many digits of output are created.
020 */
021 int
022 s_mp_mul_digs (mp_int * a, mp_int * b, mp_int * c, int digs)
023 {
024     mp_int t;
025     int     res, pa, pb, ix, iy;
026     mp_digit u;
027     mp_word r;
028     mp_digit tmpx, *tmpt, *tmpy;
029
030     /* can we use the fast multiplier? */
031     if (((digs) < MP_WARRAY) &&
032         MIN (a->used, b->used) <
033             (1 << ((CHAR_BIT * sizeof (mp_word)) - (2 * DIGIT_BIT)))) {
034         return fast_s_mp_mul_digs (a, b, c, digs);
035     }
036
037     if ((res = mp_init_size (&t, digs)) != MP_OKAY) {
038         return res;
039     }
040     t.used = digs;
041
042     /* compute the digits of the product directly */
043     pa = a->used;
044     for (ix = 0; ix < pa; ix++) {
045         /* set the carry to zero */
046         u = 0;
047
048         /* limit ourselves to making digs digits of output */
049         pb = MIN (b->used, digs - ix);
050
051         /* setup some aliases */
052         /* copy of the digit from a used within the nested loop */
053         tmpx = a->dp[ix];
054

```

```

055     /* an alias for the destination shifted ix places */
056     tmp = t.dp + ix;
057
058     /* an alias for the digits of b */
059     tmpy = b->dp;
060
061     /* compute the columns of the output and propagate the carry */
062     for (iy = 0; iy < pb; iy++) {
063         /* compute the column as a mp_word */
064         r      = ((mp_word)*tmp) +
065                 ((mp_word)tmpx) * ((mp_word)*tmpy++) +
066                 ((mp_word) u);
067
068         /* the new column is the lower part of the result */
069         *tmp++ = (mp_digit) (r & ((mp_word) MP_MASK));
070
071         /* get the carry word from the result */
072         u      = (mp_digit) (r >> ((mp_word) DIGIT_BIT));
073     }
074     /* set carry if it is placed below digs */
075     if (ix + iy < digs) {
076         *tmp = u;
077     }
078 }
079
080 mp_clamp (&t);
081 mp_exch (&t, c);
082
083 mp_clear (&t);
084 return MP_OKAY;
085 }

```

Lines 31 to 35 determine if the Comba method can be used first. The conditions for using the Comba routine are that $\min(a.used, b.used) < \delta$ and the number of digits of output is less than **MP_WARRAY**. This new constant is used to control the stack usage in the Comba routines. By default it is set to δ but can be reduced when memory is at a premium.

Of particular importance is the calculation of the $ix + iy$ 'th column on lines 64, 65 and 66. Note how all of the variables are cast to the type **mp_word**, which is also the type of variable \hat{r} . That is to ensure that double precision operations are used instead of single precision. The multiplication on line 65 makes use of a specific GCC optimizer behaviour. On the outset it looks like the

compiler will have to use a double precision multiplication to produce the result required. Such an operation would be horribly slow on most processors and drag this to a crawl. However, GCC is smart enough to realize that double wide output single precision multipliers can be used. For example, the instruction “MUL” on the x86 processor can multiply two 32-bit values and produce a 64-bit result.

5.2.2 Faster Multiplication by the “Comba” Method

One of the huge drawbacks of the “baseline” algorithms is that at the $O(n^2)$ level the carry must be computed and propagated upwards. This makes the nested loop very sequential and hard to unroll and implement in parallel. The “Comba” [4] method is named after little known (*in cryptographic venues*) Paul G. Comba who described a method of implementing fast multipliers that do not require nested carry fixup operations. As an interesting aside it seems that Paul Barrett describes a similar technique in his 1986 paper [7] written five years before.

At the heart of the Comba technique is once again the long-hand algorithm. Except in this case a slight twist is placed on how the columns of the result are produced. In the standard long-hand algorithm rows of products are produced then added together to form the final result. In the baseline algorithm the columns are added together after each iteration to get the result instantaneously.

In the Comba algorithm the columns of the result are produced entirely independently of each other. That is at the $O(n^2)$ level a simple multiplication and addition step is performed. The carries of the columns are propagated after the nested loop to reduce the amount of work required. Succinctly the first step of the algorithm is to compute the product vector \vec{x} as follows.

$$\vec{x}_n = \sum_{i+j=n} a_i b_j, \forall n \in \{0, 1, 2, \dots, i + j\} \quad (5.1)$$

Where \vec{x}_n is the n 'th column of the output vector. Consider the following example which computes the vector \vec{x} for the multiplication of 576 and 241.

		5	7	6	First Input
\times		2	4	1	Second Input
		$1 \cdot 5 = 5$	$1 \cdot 7 = 7$	$1 \cdot 6 = 6$	First pass
	$4 \cdot 5 = 20$	$4 \cdot 7 + 5 = 33$	$4 \cdot 6 + 7 = 31$	6	Second pass
$2 \cdot 5 = 10$	$2 \cdot 7 + 20 = 34$	$2 \cdot 6 + 33 = 45$	31	6	Third pass
10	34	45	31	6	Final Result

Figure 5.3: Comba Multiplication Diagram

At this point the vector $x = \langle 10, 34, 45, 31, 6 \rangle$ is the result of the first step of the Comba multiplier. Now the columns must be fixed by propagating the carry upwards. The resultant vector will have one extra dimension over the input vector which is congruent to adding a leading zero digit.

Algorithm Comba Fixup.

Input. Vector \vec{x} of dimension k

Output. Vector \vec{x} such that the carries have been propagated.

1. for n from 0 to $k - 1$ do
 - 1.1 $\vec{x}_{n+1} \leftarrow \vec{x}_{n+1} + \lfloor \vec{x}_n / \beta \rfloor$
 - 1.2 $\vec{x}_n \leftarrow \vec{x}_n \pmod{\beta}$
 2. Return(\vec{x}).
-

Figure 5.4: Algorithm Comba Fixup

With that algorithm and $k = 5$ and $\beta = 10$ the following vector is produced $\vec{x} = \langle 1, 3, 8, 8, 1, 6 \rangle$. In this case $241 \cdot 576$ is in fact 138816 and the procedure succeeded. If the algorithm is correct and as will be demonstrated shortly more efficient than the baseline algorithm why not simply always use this algorithm?

Column Weight.

At the nested $O(n^2)$ level the Comba method adds the product of two single precision variables to each column of the output independently. A serious obstacle is if the carry is lost, due to lack of precision before the algorithm has a chance to fix the carries. For example, in the multiplication of two three-digit numbers the third column of output will be the sum of three single precision multiplications. If the precision of the accumulator for the output digits is less than $3 \cdot (\beta - 1)^2$ then an overflow can occur and the carry information will be lost.

For any m and n digit inputs the maximum weight of any column is $\min(m, n)$ which is fairly obvious.

The maximum number of terms in any column of a product is known as the “column weight” and strictly governs when the algorithm can be used. Recall from earlier that a double precision type has α bits of resolution and a single precision digit has $lg(\beta)$ bits of precision. Given these two quantities we must not violate the following

$$k \cdot (\beta - 1)^2 < 2^\alpha \quad (5.2)$$

Which reduces to

$$k \cdot (\beta^2 - 2\beta + 1) < 2^\alpha \quad (5.3)$$

Let $\rho = lg(\beta)$ represent the number of bits in a single precision digit. By further re-arrangement of the equation the final solution is found.

$$k < \frac{2^\alpha}{(2^{2\rho} - 2^{\rho+1} + 1)} \quad (5.4)$$

The defaults for LibTomMath are $\beta = 2^{28}$ and $\alpha = 2^{64}$ which means that k is bounded by $k < 257$. In this configuration the smaller input may not have more than 256 digits if the Comba method is to be used. This is quite satisfactory for most applications since 256 digits would allow for numbers in the range of $0 \leq x < 2^{7168}$ which, is much larger than most public key cryptographic algorithms require.

Algorithm **fast_s_mp_mul_digs**.

Input. mp_int a , mp_int b and an integer $digs$

Output. $c \leftarrow |a| \cdot |b| \pmod{\beta^{digs}}$.

Place an array of **MP_WARRAY** double precision digits named \hat{W} on the stack.

1. If $c.alloc < digs$ then grow c to $digs$ digits. (*mp_grow*)
2. If step 1 failed return(*MP_MEM*).

Zero the temporary array \hat{W} .

3. for n from 0 to $digs - 1$ do
 - 3.1 $\hat{W}_n \leftarrow 0$

Compute the columns.

4. for ix from 0 to $a.used - 1$ do
 - 4.1 $pb \leftarrow \min(b.used, digs - ix)$
 - 4.2 If $pb < 1$ then goto step 5.
 - 4.3 for iy from 0 to $pb - 1$ do
 - 4.3.1 $\hat{W}_{ix+iy} \leftarrow \hat{W}_{ix+iy} + a_{ix}b_{iy}$

Propagate the carries upwards.

5. $oldused \leftarrow c.used$
6. $c.used \leftarrow digs$
7. If $digs > 1$ then do
 - 7.1. for ix from 1 to $digs - 1$ do
 - 7.1.1 $\hat{W}_{ix} \leftarrow \hat{W}_{ix} + \lfloor \hat{W}_{ix-1} / \beta \rfloor$
 - 7.1.2 $c_{ix-1} \leftarrow \hat{W}_{ix-1} \pmod{\beta}$
8. else do
 - 8.1 $ix \leftarrow 0$
9. $c_{ix} \leftarrow \hat{W}_{ix} \pmod{\beta}$

Zero excess digits.

10. If $digs < oldused$ then do
 - 10.1 for n from $digs$ to $oldused - 1$ do
 - 10.1.1 $c_n \leftarrow 0$
 11. Clamp excessive digits of c . (*mp_clamp*)
 12. Return(*MP_OKAY*).
-

Figure 5.5: Algorithm fast_s_mp_mul_digs

Algorithm fast_s_mp_mul_digs. This algorithm performs the unsigned

multiplication of a and b using the Comba method limited to $digs$ digits of precision. The algorithm essentially performs the same calculation as algorithm `s_mp_mul_digs`, just much faster.

The array \hat{W} is meant to be on the stack when the algorithm is used. The size of the array does not change which is ideal. Note also that unlike algorithm `s_mp_mul_digs` no temporary `mp_int` is required since the result is calculated directly in \hat{W} .

The $O(n^2)$ loop on step four is where the Comba method's advantages begin to show through in comparison to the baseline algorithm. The lack of a carry variable or propagation in this loop allows the loop to be performed with only single precision multiplication and additions. Now that each iteration of the inner loop can be performed independent of the others the inner loop can be performed with a high level of parallelism.

To measure the benefits of the Comba method over the baseline method consider the number of operations that are required. If the cost in terms of time of a multiply and addition is p and the cost of a carry propagation is q then a baseline multiplication would require $O((p+q)n^2)$ time to multiply two n -digit numbers. The Comba method requires only $O(pn^2 + qn)$ time, however in practice, the speed increase is actually much more. With $O(n)$ space the algorithm can be reduced to $O(pn + qn)$ time by implementing the n multiply and addition operations in the nested loop in parallel.

File: `bn_fast_s_mp_mul_digs.c`

```

016
017  /* Fast (comba) multiplier
018  *
019  * This is the fast column-array [comba] multiplier. It is
020  * designed to compute the columns of the product first
021  * then handle the carries afterwards. This has the effect
022  * of making the nested loops that compute the columns very
023  * simple and schedulable on super-scalar processors.
024  *
025  * This has been modified to produce a variable number of
026  * digits of output so if say only a half-product is required
027  * you don't have to compute the upper half (a feature
028  * required for fast Barrett reduction).
029  *
030  * Based on Algorithm 14.12 on pp.595 of HAC.
031  *
032  */
033  int
```

```
034 fast_s_mp_mul_digs (mp_int * a, mp_int * b, mp_int * c, int digs)
035 {
036     int      olduse, res, pa, ix;
037     mp_word W[MP_WARRAY];
038
039     /* grow the destination as required */
040     if (c->alloc < digs) {
041         if ((res = mp_grow (c, digs)) != MP_OKAY) {
042             return res;
043         }
044     }
045
046     /* clear temp buf (the columns) */
047     memset (W, 0, sizeof (mp_word) * digs);
048
049     /* calculate the columns */
050     pa = a->used;
051     for (ix = 0; ix < pa; ix++) {
052         /* this multiplier has been modified to allow you to
053          * control how many digits of output are produced.
054          * So at most we want to make upto "digs" digits of output.
055          *
056          * this adds products to distinct columns (at ix+iy) of W
057          * note that each step through the loop is not dependent on
058          * the previous which means the compiler can easily unroll
059          * the loop without scheduling problems
060          */
061         {
062             register mp_digit tmpx, *tmpy;
063             register mp_word *_W;
064             register int iy, pb;
065
066             /* alias for the the word on the left e.g. A[ix] * A[iy] */
067             tmpx = a->dp[ix];
068
069             /* alias for the right side */
070             tmpy = b->dp;
071
072             /* alias for the columns, each step through the loop adds a new
073              term to each column
074              */
075             _W = W + ix;
```

```

076
077     /* the number of digits is limited by their placement.  E.g.
078         we avoid multiplying digits that will end up above the # of
079         digits of precision requested
080     */
081     pb = MIN (b->used, digs - ix);
082
083     for (iy = 0; iy < pb; iy++) {
084         *_W++ += ((mp_word)tmpx) * ((mp_word)*tmpy++);
085     }
086 }
087
088 }
089
090 /* setup dest */
091 olduse = c->used;
092 c->used = digs;
093
094 {
095     register mp_digit *tmpc;
096
097     /* At this point W[] contains the sums of each column.  To get the
098     * correct result we must take the extra bits from each column and
099     * carry them down
100     *
101     * Note that while this adds extra code to the multiplier it
102     * saves time since the carry propagation is removed from the
103     * above nested loop. This has the effect of reducing the work
104     * from  $N*(N+N*c) = N**2 + c*N**2$  to  $N**2 + N*c$  where  $c$  is the
105     * cost of the shifting.  On very small numbers this is slower
106     * but on most cryptographic size numbers it is faster.
107     *
108     * In this particular implementation we feed the carries from
109     * behind which means when the loop terminates we still have one
110     * last digit to copy
111     */
112     tmpc = c->dp;
113     for (ix = 1; ix < digs; ix++) {
114         /* forward the carry from the previous temp */
115         W[ix] += (W[ix - 1] >> ((mp_word) DIGIT_BIT));
116
117         /* now extract the previous digit [below the carry] */

```

```

118     *tmpc++ = (mp_digit) (W[ix - 1] & ((mp_word) MP_MASK));
119     }
120     /* fetch the last digit */
121     *tmpc++ = (mp_digit) (W[digs - 1] & ((mp_word) MP_MASK));
122
123     /* clear unused digits [that existed in the old copy of c] */
124     for (; ix < olduse; ix++) {
125         *tmpc++ = 0;
126     }
127     }
128     mp_clamp (c);
129     return MP_OKAY;
130 }

```

The memset on line 47 clears the initial \hat{W} array to zero in a single step. Like the slower baseline multiplication implementation a series of aliases (*lines 67, 70 and 75*) are used to simplify the inner $O(n^2)$ loop. In this case a new alias $_W$ has been added which refers to the double precision columns offset by ix in each pass.

The inner loop on lines 83, 84 and 85 is where the algorithm will spend the majority of the time, which is why it has been stripped to the bones of any extra baggage². On x86 processors the multiplication and additions amount to at the very least five instructions (*two loads, two additions, one multiply*) while on the ARMv4 processors they amount to only three (*one load, one store, one multiply-add*). For both of the x86 and ARMv4 processors the GCC compiler performs a good job at unrolling the loop and scheduling the instructions so there are very few dependency stalls.

In theory the difference between the baseline and comba algorithms is a mere $O(qn)$ time difference. However, in the $O(n^2)$ nested loop of the baseline method there are dependency stalls as the algorithm must wait for the multiplier to finish before propagating the carry to the next digit. As a result fewer of the often multiple execution units³ can be simultaneously used.

5.2.3 Polynomial Basis Multiplication

To break the $O(n^2)$ barrier in multiplication requires a completely different look at integer multiplication. In the following algorithms the use of polynomial basis representation for two integers a and b as $f(x) = \sum_{i=0}^n a_i x^i$ and $g(x) =$

²Hence the pointer aliases.

³The AMD Athlon has three execution units and the Intel P4 has four.

$\sum_{i=0}^n b_i x^i$ respectively, is required. In this system both $f(x)$ and $g(x)$ have $n+1$ terms and are of the n 'th degree.

The product $a \cdot b \equiv f(x)g(x)$ is the polynomial $W(x) = \sum_{i=0}^{2n} w_i x^i$. The coefficients w_i will directly yield the desired product when β is substituted for x . The direct solution to solve for the $2n+1$ coefficients requires $O(n^2)$ time and would in practice be slower than the Comba technique.

However, numerical analysis theory indicates that only $2n+1$ distinct points in $W(x)$ are required to determine the values of the $2n+1$ unknown coefficients. This means by finding $\zeta_y = W(y)$ for $2n+1$ small values of y the coefficients of $W(x)$ can be found with Gaussian elimination. This technique is also occasionally referred to as the *interpolation technique* (*references please...*) since in effect an interpolation based on $2n+1$ points will yield a polynomial equivalent to $W(x)$.

The coefficients of the polynomial $W(x)$ are unknown which makes finding $W(y)$ for any value of y impossible. However, since $W(x) = f(x)g(x)$ the equivalent $\zeta_y = f(y)g(y)$ can be used in its place. The benefit of this technique stems from the fact that $f(y)$ and $g(y)$ are much smaller than either a or b respectively. As a result finding the $2n+1$ relations required by multiplying $f(y)g(y)$ involves multiplying integers that are much smaller than either of the inputs.

When picking points to gather relations there are always three obvious points to choose, $y = 0, 1$ and ∞ . The ζ_0 term is simply the product $W(0) = w_0 = a_0 \cdot b_0$. The ζ_1 term is the product $W(1) = (\sum_{i=0}^n a_i)(\sum_{i=0}^n b_i)$. The third point ζ_∞ is less obvious but rather simple to explain. The $2n+1$ 'th coefficient of $W(x)$ is numerically equivalent to the most significant column in an integer multiplication. The point at ∞ is used symbolically to represent the most significant column, that is $W(\infty) = w_{2n} = a_n b_n$. Note that the points at $y = 0$ and ∞ yield the coefficients w_0 and w_{2n} directly.

If more points are required they should be of small values and powers of two such as 2^q and the related *mirror points* $(2^q)^{2n} \cdot \zeta_{2^{-q}}$ for small values of q . The term "mirror point" stems from the fact that $(2^q)^{2n} \cdot \zeta_{2^{-q}}$ can be calculated in the exact opposite fashion as ζ_{2^q} . For example, when $n = 2$ and $q = 1$ then following two equations are equivalent to the point ζ_2 and its mirror.

$$\begin{aligned} \zeta_2 &= f(2)g(2) = (4a_2 + 2a_1 + a_0)(4b_2 + 2b_1 + b_0) \\ 16 \cdot \zeta_{\frac{1}{2}} &= 4f\left(\frac{1}{2}\right) \cdot 4g\left(\frac{1}{2}\right) = (a_2 + 2a_1 + 4a_0)(b_2 + 2b_1 + 4b_0) \end{aligned} \quad (5.5)$$

Using such points will allow the values of $f(y)$ and $g(y)$ to be independently

Split into n Parts	Exponent	Notes
2	1.584962501	This is Karatsuba Multiplication.
3	1.464973520	This is Toom-Cook Multiplication.
4	1.403677461	
5	1.365212389	
10	1.278753601	
100	1.149426538	
1000	1.100270931	
10000	1.075252070	

Figure 5.6: Asymptotic Running Time of Polynomial Basis Multiplication

calculated using only left shifts. For example, when $n = 2$ the polynomial $f(2^q)$ is equal to $2^q((2^q a_2) + a_1) + a_0$. This technique of polynomial representation is known as Horner's method.

As a general rule of the algorithm when the inputs are split into n parts each there are $2n - 1$ multiplications. Each multiplication is of multiplicands that have n times fewer digits than the inputs. The asymptotic running time of this algorithm is $O(k^{lg_n(2n-1)})$ for k digit inputs (*assuming they have the same number of digits*). Figure 5.6 summarizes the exponents for various values of n .

At first it may seem like a good idea to choose $n = 1000$ since the exponent is approximately 1.1. However, the overhead of solving for the 2001 terms of $W(x)$ will certainly consume any savings the algorithm could offer for all but exceedingly large numbers.

Cutoff Point

The polynomial basis multiplication algorithms all require fewer single precision multiplications than a straight Comba approach. However, the algorithms incur an overhead (*at the $O(n)$ work level*) since they require a system of equations to be solved. This makes the polynomial basis approach more costly to use with small inputs.

Let m represent the number of digits in the multiplicands (*assume both multiplicands have the same number of digits*). There exists a point y such that when $m < y$ the polynomial basis algorithms are more costly than Comba, when $m = y$ they are roughly the same cost and when $m > y$ the Comba methods are slower than the polynomial basis algorithms.

The exact location of y depends on several key architectural elements of the computer platform in question.

1. The ratio of clock cycles for single precision multiplication versus other simpler operations such as addition, shifting, etc. For example on the AMD Athlon the ratio is roughly 17 : 1 while on the Intel P4 it is 29 : 1. The higher the ratio in favour of multiplication the lower the cutoff point y will be.
2. The complexity of the linear system of equations (*for the coefficients of $W(x)$*) is. Generally speaking as the number of splits grows the complexity grows substantially. Ideally solving the system will only involve addition, subtraction and shifting of integers. This directly reflects on the ratio previously mentioned.
3. To a lesser extent memory bandwidth and function call overheads. Provided the values are in the processor cache this is less of an influence over the cutoff point.

A clean cutoff point separation occurs when a point y is found such that all of the cutoff point conditions are met. For example, if the point is too low then there will be values of m such that $m > y$ and the Comba method is still faster. Finding the cutoff points is fairly simple when a high resolution timer is available.

5.2.4 Karatsuba Multiplication

Karatsuba [5] multiplication when originally proposed in 1962 was among the first set of algorithms to break the $O(n^2)$ barrier for general purpose multiplication. Given two polynomial basis representations $f(x) = ax + b$ and $g(x) = cx + d$, Karatsuba proved with light algebra [6] that the following polynomial is equivalent to multiplication of the two integers the polynomials represent.

$$f(x) \cdot g(x) = acx^2 + ((a - b)(c - d) + ac + bd)x + bd \quad (5.6)$$

Using the observation that ac and bd could be re-used only three half sized multiplications would be required to produce the product. Applying this algorithm recursively, the work factor becomes $O(n^{\lg(3)})$ which is substantially better than the work factor $O(n^2)$ of the Comba technique. It turns out what

Karatsuba did not know or at least did not publish was that this is simply polynomial basis multiplication with the points ζ_0 , ζ_∞ and $-\zeta_{-1}$. Consider the resultant system of equations.

$$\begin{array}{rcl} \zeta_0 & = & w_0 \\ -\zeta_{-1} & = & -w_2 + w_1 - w_0 \\ \zeta_\infty & = & w_2 \end{array}$$

By adding the first and last equation to the equation in the middle the term w_1 can be isolated and all three coefficients solved for. The simplicity of this system of equations has made Karatsuba fairly popular. In fact the cutoff point is often fairly low⁴ making it an ideal algorithm to speed up certain public key cryptosystems such as RSA and Diffie-Hellman. It is worth noting that the point ζ_1 could be substituted for $-\zeta_{-1}$. In this case the first and third row are subtracted instead of added to the second row.

⁴With LibTomMath 0.18 it is 70 and 109 digits for the Intel P4 and AMD Athlon respectively.

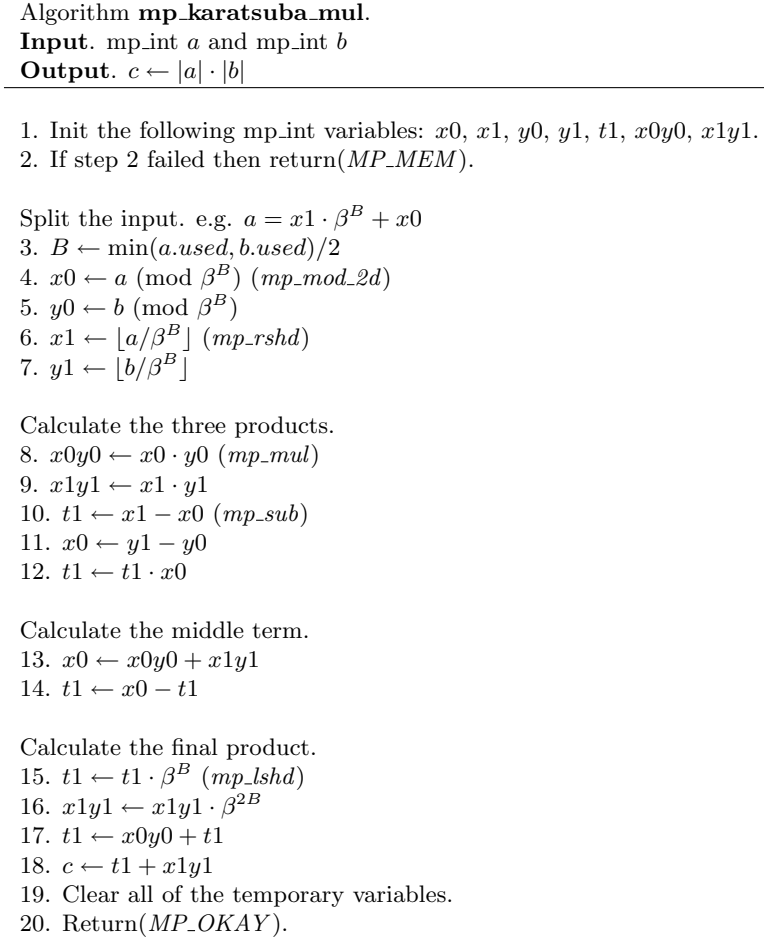


Figure 5.7: Algorithm mp_karatsuba_mul

Algorithm mp_karatsuba_mul. This algorithm computes the unsigned product of two inputs using the Karatsuba multiplication algorithm. It is loosely based on the description from Knuth [1, pp. 294-295].

In order to split the two inputs into their respective halves, a suitable *radix point* must be chosen. The radix point chosen must be used for both of the

inputs meaning that it must be smaller than the smallest input. Step 3 chooses the radix point B as half of the smallest input `used` count. After the radix point is chosen the inputs are split into lower and upper halves. Step 4 and 5 compute the lower halves. Step 6 and 7 compute the upper halves.

After the halves have been computed the three intermediate half-size products must be computed. Step 8 and 9 compute the trivial products $x_0 \cdot y_0$ and $x_1 \cdot y_1$. The `mp_int` x_0 is used as a temporary variable after $x_1 - x_0$ has been computed. By using x_0 instead of an additional temporary variable, the algorithm can avoid an addition memory allocation operation.

The remaining steps 13 through 18 compute the Karatsuba polynomial through a variety of digit shifting and addition operations.

File: `bn_mp_karatsuba_mul.c`

```

016
017 /* c = |a| * |b| using Karatsuba Multiplication using
018 * three half size multiplications
019 *
020 * Let B represent the radix [e.g. 2**DIGIT_BIT] and
021 * let n represent half of the number of digits in
022 * the min(a,b)
023 *
024 * a = a1 * B**n + a0
025 * b = b1 * B**n + b0
026 *
027 * Then, a * b =>
028     a1b1 * B**2n + ((a1 - a0)(b1 - b0) + a0b0 + a1b1) * B + a0b0
029 *
030 * Note that a1b1 and a0b0 are used twice and only need to be
031 * computed once. So in total three half size (half # of
032 * digit) multiplications are performed, a0b0, a1b1 and
033 * (a1-b1)(a0-b0)
034 *
035 * Note that a multiplication of half the digits requires
036 * 1/4th the number of single precision multiplications so in
037 * total after one call 25% of the single precision multiplications
038 * are saved. Note also that the call to mp_mul can end up back
039 * in this function if the a0, a1, b0, or b1 are above the threshold.
040 * This is known as divide-and-conquer and leads to the famous
041 *  $O(N \cdot \lg(3))$  or  $O(N \cdot 1.584)$  work which is asymptotically lower than
042 * the standard  $O(N^2)$  that the baseline/comba methods use.
043 * Generally though the overhead of this method doesn't pay off
044 * until a certain size ( $N \sim 80$ ) is reached.
```

```
045  */
046  int
047  mp_karatsuba_mul (mp_int * a, mp_int * b, mp_int * c)
048  {
049      mp_int  x0, x1, y0, y1, t1, x0y0, x1y1;
050      int     B, err;
051
052      /* default the return code to an error */
053      err = MP_MEM;
054
055      /* min # of digits */
056      B = MIN (a->used, b->used);
057
058      /* now divide in two */
059      B = B / 2;
060
061      /* init copy all the temps */
062      if (mp_init_size (&x0, B) != MP_OKAY)
063          goto ERR;
064      if (mp_init_size (&x1, a->used - B) != MP_OKAY)
065          goto X0;
066      if (mp_init_size (&y0, B) != MP_OKAY)
067          goto X1;
068      if (mp_init_size (&y1, b->used - B) != MP_OKAY)
069          goto Y0;
070
071      /* init temps */
072      if (mp_init_size (&t1, B * 2) != MP_OKAY)
073          goto Y1;
074      if (mp_init_size (&x0y0, B * 2) != MP_OKAY)
075          goto T1;
076      if (mp_init_size (&x1y1, B * 2) != MP_OKAY)
077          goto XOY0;
078
079      /* now shift the digits */
080      x0.sign = x1.sign = a->sign;
081      y0.sign = y1.sign = b->sign;
082
083      x0.used = y0.used = B;
084      x1.used = a->used - B;
085      y1.used = b->used - B;
086
```

```

087     {
088         register int x;
089         register mp_digit *tmpa, *tmpb, *tmpx, *tmpy;
090
091         /* we copy the digits directly instead of using higher level functions
092          * since we also need to shift the digits
093          */
094         tmpa = a->dp;
095         tmpb = b->dp;
096
097         tmpx = x0.dp;
098         tmpy = y0.dp;
099         for (x = 0; x < B; x++) {
100             *tmpx++ = *tmpa++;
101             *tmpy++ = *tmpb++;
102         }
103
104         tmpx = x1.dp;
105         for (x = B; x < a->used; x++) {
106             *tmpx++ = *tmpa++;
107         }
108
109         tmpy = y1.dp;
110         for (x = B; x < b->used; x++) {
111             *tmpy++ = *tmpb++;
112         }
113     }
114
115     /* only need to clamp the lower words since by definition the
116      * upper words x1/y1 must have a known number of digits
117      */
118     mp_clamp (&x0);
119     mp_clamp (&y0);
120
121     /* now calc the products x0y0 and x1y1 */
122     /* after this x0 is no longer required, free temp [x0==t2]! */
123     if (mp_mul (&x0, &y0, &x0y0) != MP_OKAY)
124         goto X1Y1;          /* x0y0 = x0*y0 */
125     if (mp_mul (&x1, &y1, &x1y1) != MP_OKAY)
126         goto X1Y1;          /* x1y1 = x1*y1 */
127
128     /* now calc x1-x0 and y1-y0 */

```

```

129     if (mp_sub (&x1, &x0, &t1) != MP_OKAY)
130         goto X1Y1;          /* t1 = x1 - x0 */
131     if (mp_sub (&y1, &y0, &x0) != MP_OKAY)
132         goto X1Y1;          /* t2 = y1 - y0 */
133     if (mp_mul (&t1, &x0, &t1) != MP_OKAY)
134         goto X1Y1;          /* t1 = (x1 - x0) * (y1 - y0) */
135
136     /* add x0y0 */
137     if (mp_add (&x0y0, &x1y1, &x0) != MP_OKAY)
138         goto X1Y1;          /* t2 = x0y0 + x1y1 */
139     if (mp_sub (&x0, &t1, &t1) != MP_OKAY)
140         goto X1Y1;          /* t1 = x0y0 + x1y1 - (x1-x0)*(y1-y0) */
141
142     /* shift by B */
143     if (mp_lshd (&t1, B) != MP_OKAY)
144         goto X1Y1;          /* t1 = (x0y0 + x1y1 - (x1-x0)*(y1-y0))<<B */
145     if (mp_lshd (&x1y1, B * 2) != MP_OKAY)
146         goto X1Y1;          /* x1y1 = x1y1 << 2*B */
147
148     if (mp_add (&x0y0, &t1, &t1) != MP_OKAY)
149         goto X1Y1;          /* t1 = x0y0 + t1 */
150     if (mp_add (&t1, &x1y1, c) != MP_OKAY)
151         goto X1Y1;          /* t1 = x0y0 + t1 + x1y1 */
152
153     /* Algorithm succeeded set the return code to MP_OKAY */
154     err = MP_OKAY;
155
156     X1Y1:mp_clear (&x1y1);
157     X0Y0:mp_clear (&x0y0);
158     T1:mp_clear (&t1);
159     Y1:mp_clear (&y1);
160     Y0:mp_clear (&y0);
161     X1:mp_clear (&x1);
162     X0:mp_clear (&x0);
163     ERR:
164     return err;
165 }

```

The new coding element in this routine, not seen in previous routines, is the usage of goto statements. The conventional wisdom is that goto statements should be avoided. This is generally true, however when every single function call can fail, it makes sense to handle error recovery with a single piece of

code. Lines 62 to 76 handle initializing all of the temporary variables required. Note how each of the if statements goes to a different label in case of failure. This allows the routine to correctly free only the temporaries that have been successfully allocated so far.

The temporary variables are all initialized using the `mp_init_size` routine since they are expected to be large. This saves the additional reallocation that would have been necessary. Also $x0$, $x1$, $y0$ and $y1$ have to be able to hold at least their respective number of digits for the next section of code.

The first algebraic portion of the algorithm is to split the two inputs into their halves. However, instead of using `mp_mod_2d` and `mp_rshd` to extract the halves, the respective code has been placed inline within the body of the function. To initialize the halves, the **used** and **sign** members are copied first. The first for loop on line 99 copies the lower halves. Since they are both the same magnitude it is simpler to calculate both lower halves in a single loop. The for loop on lines 105 and 110 calculate the upper halves $x1$ and $y1$ respectively.

By inlining the calculation of the halves, the Karatsuba multiplier has a slightly lower overhead and can be used for smaller magnitude inputs.

When line 154 is reached, the algorithm has completed successfully. The “error status” variable `err` is set to **MP_OKAY** so that the same code that handles errors can be used to clear the temporary variables and return.

5.2.5 Toom-Cook 3-Way Multiplication

Toom-Cook 3-Way [?] multiplication is essentially the polynomial basis algorithm for $n = 2$ except that the points are chosen such that ζ is easy to compute and the resulting system of equations easy to reduce. Here, the points ζ_0 , $16 \cdot \zeta_{\frac{1}{2}}$, ζ_1 , ζ_2 and ζ_∞ make up the five required points to solve for the coefficients of the $W(x)$.

With the five relations that Toom-Cook specifies, the following system of equations is formed.

$$\begin{array}{rcll}
 \zeta_0 & = & 0w_4 & + & 0w_3 & + & 0w_2 & + & 0w_1 & + & 1w_0 \\
 16 \cdot \zeta_{\frac{1}{2}} & = & 1w_4 & + & 2w_3 & + & 4w_2 & + & 8w_1 & + & 16w_0 \\
 \zeta_1 & = & 1w_4 & + & 1w_3 & + & 1w_2 & + & 1w_1 & + & 1w_0 \\
 \zeta_2 & = & 16w_4 & + & 8w_3 & + & 4w_2 & + & 2w_1 & + & 1w_0 \\
 \zeta_\infty & = & 1w_4 & + & 0w_3 & + & 0w_2 & + & 0w_1 & + & 0w_0
 \end{array}$$

A trivial solution to this matrix requires 12 subtractions, two multiplications by a small power of two, two divisions by a small power of two, two divisions

by three and one multiplication by three. All of these 19 sub-operations require less than quadratic time, meaning that the algorithm can be faster than a baseline multiplication. However, the greater complexity of this algorithm places the cutoff point (**TOOM_MUL_CUTOFF**) where Toom-Cook becomes more efficient much higher than the Karatsuba cutoff point.

Algorithm **mp_toom_mul**.

Input. mp_int a and mp_int b

Output. $c \leftarrow a \cdot b$

Split a and b into three pieces. E.g. $a = a_2\beta^{2k} + a_1\beta^k + a_0$

1. $k \leftarrow \lfloor \min(a.used, b.used)/3 \rfloor$
2. $a_0 \leftarrow a \pmod{\beta^k}$
3. $a_1 \leftarrow \lfloor a/\beta^k \rfloor$, $a_1 \leftarrow a_1 \pmod{\beta^k}$
4. $a_2 \leftarrow \lfloor a/\beta^{2k} \rfloor$, $a_2 \leftarrow a_2 \pmod{\beta^k}$
5. $b_0 \leftarrow b \pmod{\beta^k}$
6. $b_1 \leftarrow \lfloor b/\beta^k \rfloor$, $b_1 \leftarrow b_1 \pmod{\beta^k}$
7. $b_2 \leftarrow \lfloor b/\beta^{2k} \rfloor$, $b_2 \leftarrow b_2 \pmod{\beta^k}$

Find the five equations for w_0, w_1, \dots, w_4 .

8. $w_0 \leftarrow a_0 \cdot b_0$
9. $w_4 \leftarrow a_2 \cdot b_2$
10. $tmp_1 \leftarrow 2 \cdot a_0$, $tmp_1 \leftarrow a_1 + tmp_1$, $tmp_1 \leftarrow 2 \cdot tmp_1$, $tmp_1 \leftarrow tmp_1 + a_2$
11. $tmp_2 \leftarrow 2 \cdot b_0$, $tmp_2 \leftarrow b_1 + tmp_2$, $tmp_2 \leftarrow 2 \cdot tmp_2$, $tmp_2 \leftarrow tmp_2 + b_2$
12. $w_1 \leftarrow tmp_1 \cdot tmp_2$
13. $tmp_1 \leftarrow 2 \cdot a_2$, $tmp_1 \leftarrow a_1 + tmp_1$, $tmp_1 \leftarrow 2 \cdot tmp_1$, $tmp_1 \leftarrow tmp_1 + a_0$
14. $tmp_2 \leftarrow 2 \cdot b_2$, $tmp_2 \leftarrow b_1 + tmp_2$, $tmp_2 \leftarrow 2 \cdot tmp_2$, $tmp_2 \leftarrow tmp_2 + b_0$
15. $w_3 \leftarrow tmp_1 \cdot tmp_2$
16. $tmp_1 \leftarrow a_0 + a_1$, $tmp_1 \leftarrow tmp_1 + a_2$, $tmp_2 \leftarrow b_0 + b_1$, $tmp_2 \leftarrow tmp_2 + b_2$
17. $w_2 \leftarrow tmp_1 \cdot tmp_2$

Continued on the next page.

Figure 5.8: Algorithm mp_toom_mul

Algorithm **mp_toom_mul** (continued).

Input. mp_int a and mp_int b

Output. $c \leftarrow a \cdot b$

Now solve the system of equations.

18. $w_1 \leftarrow w_4 - w_1, w_3 \leftarrow w_3 - w_0$

19. $w_1 \leftarrow \lfloor w_1/2 \rfloor, w_3 \leftarrow \lfloor w_3/2 \rfloor$

20. $w_2 \leftarrow w_2 - w_0, w_2 \leftarrow w_2 - w_4$

21. $w_1 \leftarrow w_1 - w_2, w_3 \leftarrow w_3 - w_2$

22. $tmp_1 \leftarrow 8 \cdot w_0, w_1 \leftarrow w_1 - tmp_1, tmp_1 \leftarrow 8 \cdot w_4, w_3 \leftarrow w_3 - tmp_1$

23. $w_2 \leftarrow 3 \cdot w_2, w_2 \leftarrow w_2 - w_1, w_2 \leftarrow w_2 - w_3$

24. $w_1 \leftarrow w_1 - w_2, w_3 \leftarrow w_3 - w_2$

25. $w_1 \leftarrow \lfloor w_1/3 \rfloor, w_3 \leftarrow \lfloor w_3/3 \rfloor$

Now substitute β^k for x by shifting w_0, w_1, \dots, w_4 .

26. for n from 1 to 4 do

26.1 $w_n \leftarrow w_n \cdot \beta^{nk}$

27. $c \leftarrow w_0 + w_1, c \leftarrow c + w_2, c \leftarrow c + w_3, c \leftarrow c + w_4$

28. Return(*MP_OKAY*)

Figure 5.9: Algorithm mp_toom_mul (continued)

Algorithm mp_toom_mul. This algorithm computes the product of two mp_int variables a and b using the Toom-Cook approach. Compared to the Karatsuba multiplication, this algorithm has a lower asymptotic running time of approximately $O(n^{1.464})$ but at an obvious cost in overhead. In this description, several statements have been compounded to save space. The intention is that the statements are executed from left to right across any given step.

The two inputs a and b are first split into three k -digit integers a_0, a_1, a_2 and b_0, b_1, b_2 respectively. From these smaller integers the coefficients of the polynomial basis representations $f(x)$ and $g(x)$ are known and can be used to find the relations required.

The first two relations w_0 and w_4 are the points ζ_0 and ζ_∞ respectively. The relation w_1, w_2 and w_3 correspond to the points $16 \cdot \zeta_{\frac{1}{2}}, \zeta_2$ and ζ_1 respectively. These are found using logical shifts to independently find $f(y)$ and $g(y)$ which significantly speeds up the algorithm.

After the five relations w_0, w_1, \dots, w_4 have been computed, the system they represent must be solved in order for the unknown coefficients w_1, w_2 and w_3 to be isolated. The steps 18 through 25 perform the system reduction required

as previously described. Each step of the reduction represents the comparable matrix operation that would be performed had this been performed by pencil. For example, step 18 indicates that row 1 must be subtracted from row 4 and simultaneously row 0 subtracted from row 3.

Once the coefficients have been isolated, the polynomial $W(x) = \sum_{i=0}^{2n} w_i x^i$ is known. By substituting β^k for x , the integer result $a \cdot b$ is produced.

File: bn_mp_toom_mul.c

```

016
017  /* multiplication using the Toom-Cook 3-way algorithm */
018  int
019  mp_toom_mul(mp_int *a, mp_int *b, mp_int *c)
020  {
021      mp_int w0, w1, w2, w3, w4, tmp1, tmp2, a0, a1, a2, b0, b1, b2;
022      int res, B;
023
024      /* init temps */
025      if ((res = mp_init_multi(&w0, &w1, &w2, &w3, &w4,
026                             &a0, &a1, &a2, &b0, &b1,
027                             &b2, &tmp1, &tmp2, NULL)) != MP_OKAY) {
028          return res;
029      }
030
031      /* B */
032      B = MIN(a->used, b->used) / 3;
033
034      /* a = a2 * B**2 + a1 * B + a0 */
035      if ((res = mp_mod_2d(a, DIGIT_BIT * B, &a0)) != MP_OKAY) {
036          goto ERR;
037      }
038
039      if ((res = mp_copy(a, &a1)) != MP_OKAY) {
040          goto ERR;
041      }
042      mp_rshd(&a1, B);
043      mp_mod_2d(&a1, DIGIT_BIT * B, &a1);
044
045      if ((res = mp_copy(a, &a2)) != MP_OKAY) {
046          goto ERR;
047      }
048      mp_rshd(&a2, B*2);
049

```

```

050      /* b = b2 * B**2 + b1 * B + b0 */
051      if ((res = mp_mod_2d(b, DIGIT_BIT * B, &b0)) != MP_OKAY) {
052          goto ERR;
053      }
054
055      if ((res = mp_copy(b, &b1)) != MP_OKAY) {
056          goto ERR;
057      }
058      mp_rshd(&b1, B);
059      mp_mod_2d(&b1, DIGIT_BIT * B, &b1);
060
061      if ((res = mp_copy(b, &b2)) != MP_OKAY) {
062          goto ERR;
063      }
064      mp_rshd(&b2, B*2);
065
066      /* w0 = a0*b0 */
067      if ((res = mp_mul(&a0, &b0, &w0)) != MP_OKAY) {
068          goto ERR;
069      }
070
071      /* w4 = a2 * b2 */
072      if ((res = mp_mul(&a2, &b2, &w4)) != MP_OKAY) {
073          goto ERR;
074      }
075
076      /* w1 = (a2 + 2(a1 + 2a0))(b2 + 2(b1 + 2b0)) */
077      if ((res = mp_mul_2(&a0, &tmp1)) != MP_OKAY) {
078          goto ERR;
079      }
080      if ((res = mp_add(&tmp1, &a1, &tmp1)) != MP_OKAY) {
081          goto ERR;
082      }
083      if ((res = mp_mul_2(&tmp1, &tmp1)) != MP_OKAY) {
084          goto ERR;
085      }
086      if ((res = mp_add(&tmp1, &a2, &tmp1)) != MP_OKAY) {
087          goto ERR;
088      }
089
090      if ((res = mp_mul_2(&b0, &tmp2)) != MP_OKAY) {
091          goto ERR;

```

```
092     }
093     if ((res = mp_add(&tmp2, &b1, &tmp2)) != MP_OKAY) {
094         goto ERR;
095     }
096     if ((res = mp_mul_2(&tmp2, &tmp2)) != MP_OKAY) {
097         goto ERR;
098     }
099     if ((res = mp_add(&tmp2, &b2, &tmp2)) != MP_OKAY) {
100         goto ERR;
101     }
102
103     if ((res = mp_mul(&tmp1, &tmp2, &w1)) != MP_OKAY) {
104         goto ERR;
105     }
106
107     /* w3 = (a0 + 2(a1 + 2a2))(b0 + 2(b1 + 2b2)) */
108     if ((res = mp_mul_2(&a2, &tmp1)) != MP_OKAY) {
109         goto ERR;
110     }
111     if ((res = mp_add(&tmp1, &a1, &tmp1)) != MP_OKAY) {
112         goto ERR;
113     }
114     if ((res = mp_mul_2(&tmp1, &tmp1)) != MP_OKAY) {
115         goto ERR;
116     }
117     if ((res = mp_add(&tmp1, &a0, &tmp1)) != MP_OKAY) {
118         goto ERR;
119     }
120
121     if ((res = mp_mul_2(&b2, &tmp2)) != MP_OKAY) {
122         goto ERR;
123     }
124     if ((res = mp_add(&tmp2, &b1, &tmp2)) != MP_OKAY) {
125         goto ERR;
126     }
127     if ((res = mp_mul_2(&tmp2, &tmp2)) != MP_OKAY) {
128         goto ERR;
129     }
130     if ((res = mp_add(&tmp2, &b0, &tmp2)) != MP_OKAY) {
131         goto ERR;
132     }
133
```

```

134     if ((res = mp_mul(&tmp1, &tmp2, &w3)) != MP_OKAY) {
135         goto ERR;
136     }
137
138
139     /* w2 = (a2 + a1 + a0)(b2 + b1 + b0) */
140     if ((res = mp_add(&a2, &a1, &tmp1)) != MP_OKAY) {
141         goto ERR;
142     }
143     if ((res = mp_add(&tmp1, &a0, &tmp1)) != MP_OKAY) {
144         goto ERR;
145     }
146     if ((res = mp_add(&b2, &b1, &tmp2)) != MP_OKAY) {
147         goto ERR;
148     }
149     if ((res = mp_add(&tmp2, &b0, &tmp2)) != MP_OKAY) {
150         goto ERR;
151     }
152     if ((res = mp_mul(&tmp1, &tmp2, &w2)) != MP_OKAY) {
153         goto ERR;
154     }
155
156     /* now solve the matrix
157
158         0  0  0  0  1
159         1  2  4  8 16
160         1  1  1  1  1
161         16 8  4  2  1
162         1  0  0  0  0
163
164     using 12 subtractions, 4 shifts,
165         2 small divisions and 1 small multiplication
166     */
167
168     /* r1 - r4 */
169     if ((res = mp_sub(&w1, &w4, &w1)) != MP_OKAY) {
170         goto ERR;
171     }
172     /* r3 - r0 */
173     if ((res = mp_sub(&w3, &w0, &w3)) != MP_OKAY) {
174         goto ERR;
175     }

```

```
176     /* r1/2 */
177     if ((res = mp_div_2(&w1, &w1)) != MP_OKAY) {
178         goto ERR;
179     }
180     /* r3/2 */
181     if ((res = mp_div_2(&w3, &w3)) != MP_OKAY) {
182         goto ERR;
183     }
184     /* r2 - r0 - r4 */
185     if ((res = mp_sub(&w2, &w0, &w2)) != MP_OKAY) {
186         goto ERR;
187     }
188     if ((res = mp_sub(&w2, &w4, &w2)) != MP_OKAY) {
189         goto ERR;
190     }
191     /* r1 - r2 */
192     if ((res = mp_sub(&w1, &w2, &w1)) != MP_OKAY) {
193         goto ERR;
194     }
195     /* r3 - r2 */
196     if ((res = mp_sub(&w3, &w2, &w3)) != MP_OKAY) {
197         goto ERR;
198     }
199     /* r1 - 8r0 */
200     if ((res = mp_mul_2d(&w0, 3, &tmp1)) != MP_OKAY) {
201         goto ERR;
202     }
203     if ((res = mp_sub(&w1, &tmp1, &w1)) != MP_OKAY) {
204         goto ERR;
205     }
206     /* r3 - 8r4 */
207     if ((res = mp_mul_2d(&w4, 3, &tmp1)) != MP_OKAY) {
208         goto ERR;
209     }
210     if ((res = mp_sub(&w3, &tmp1, &w3)) != MP_OKAY) {
211         goto ERR;
212     }
213     /* 3r2 - r1 - r3 */
214     if ((res = mp_mul_d(&w2, 3, &w2)) != MP_OKAY) {
215         goto ERR;
216     }
217     if ((res = mp_sub(&w2, &w1, &w2)) != MP_OKAY) {
```

```

218         goto ERR;
219     }
220     if ((res = mp_sub(&w2, &w3, &w2)) != MP_OKAY) {
221         goto ERR;
222     }
223     /* r1 - r2 */
224     if ((res = mp_sub(&w1, &w2, &w1)) != MP_OKAY) {
225         goto ERR;
226     }
227     /* r3 - r2 */
228     if ((res = mp_sub(&w3, &w2, &w3)) != MP_OKAY) {
229         goto ERR;
230     }
231     /* r1/3 */
232     if ((res = mp_div_3(&w1, &w1, NULL)) != MP_OKAY) {
233         goto ERR;
234     }
235     /* r3/3 */
236     if ((res = mp_div_3(&w3, &w3, NULL)) != MP_OKAY) {
237         goto ERR;
238     }
239
240     /* at this point shift W[n] by B*n */
241     if ((res = mp_lshd(&w1, 1*B)) != MP_OKAY) {
242         goto ERR;
243     }
244     if ((res = mp_lshd(&w2, 2*B)) != MP_OKAY) {
245         goto ERR;
246     }
247     if ((res = mp_lshd(&w3, 3*B)) != MP_OKAY) {
248         goto ERR;
249     }
250     if ((res = mp_lshd(&w4, 4*B)) != MP_OKAY) {
251         goto ERR;
252     }
253
254     if ((res = mp_add(&w0, &w1, c)) != MP_OKAY) {
255         goto ERR;
256     }
257     if ((res = mp_add(&w2, &w3, &tmp1)) != MP_OKAY) {
258         goto ERR;
259     }

```



```
260     if ((res = mp_add(&w4, &tmp1, &tmp1)) != MP_OKAY) {
261         goto ERR;
262     }
263     if ((res = mp_add(&tmp1, c, c)) != MP_OKAY) {
264         goto ERR;
265     }
266
267 ERR:
268     mp_clear_multi(&w0, &w1, &w2, &w3, &w4,
269                  &a0, &a1, &a2, &b0, &b1,
270                  &b2, &tmp1, &tmp2, NULL);
271     return res;
272 }
273
```

– Comments to be added during editing phase.

5.2.6 Signed Multiplication

Now that algorithms to handle multiplications of every useful dimensions have been developed, a rather simple finishing touch is required. So far all of the multiplication algorithms have been unsigned multiplications which leaves only a signed multiplication algorithm to be established.

Algorithm **mp_mul**.

Input. mp_int a and mp_int b

Output. $c \leftarrow a \cdot b$

1. If $a.sign = b.sign$ then
 - 1.1 $sign = MP_ZPOS$
 2. else
 - 2.1 $sign = MP_ZNEG$
 3. If $\min(a.used, b.used) \geq TOOM_MUL_CUTOFF$ then
 - 3.1 $c \leftarrow a \cdot b$ using algorithm mp_toom_mul
 4. else if $\min(a.used, b.used) \geq KARATSUBA_MUL_CUTOFF$ then
 - 4.1 $c \leftarrow a \cdot b$ using algorithm mp_karatsuba_mul
 5. else
 - 5.1 $digs \leftarrow a.used + b.used + 1$
 - 5.2 If $digs < MP_ARRAY$ and $\min(a.used, b.used) \leq \delta$ then
 - 5.2.1 $c \leftarrow a \cdot b \pmod{\beta^{digs}}$ using algorithm fast_s_mp_mul_digs.
 - 5.3 else
 - 5.3.1 $c \leftarrow a \cdot b \pmod{\beta^{digs}}$ using algorithm s_mp_mul_digs.
 6. $c.sign \leftarrow sign$
 7. Return the result of the unsigned multiplication performed.
-

Figure 5.10: Algorithm mp_mul

Algorithm mp_mul. This algorithm performs the signed multiplication of two inputs. It will make use of any of the three unsigned multiplication algorithms available when the input is of appropriate size. The **sign** of the result is not set until the end of the algorithm since algorithm s_mp_mul_digs will clear it.

File: bn_mp_mul.c

```

016
017 /* high level multiplication (handles sign) */
018 int mp_mul (mp_int * a, mp_int * b, mp_int * c)
019 {
020     int    res, neg;
021     neg = (a->sign == b->sign) ? MP_ZPOS : MP_NEG;
022
023     /* use Toom-Cook? */
024     if (MIN (a->used, b->used) >= TOOM_MUL_CUTOFF) {
025         res = mp_toom_mul(a, b, c);
026     /* use Karatsuba? */

```

```

027     } else if (MIN (a->used, b->used) >= KARATSUBA_MUL_CUTOFF) {
028         res = mp_karatsuba_mul (a, b, c);
029     } else {
030         /* can we use the fast multiplier?
031          *
032          * The fast multiplier can be used if the output will
033          * have less than MP_WARRAY digits and the number of
034          * digits won't affect carry propagation
035          */
036         int     digs = a->used + b->used + 1;
037
038         if ((digs < MP_WARRAY) &&
039             MIN(a->used, b->used) <=
040             (1 << ((CHAR_BIT * sizeof (mp_word)) - (2 * DIGIT_BIT)))) {
041             res = fast_s_mp_mul_digs (a, b, c, digs);
042         } else {
043             res = s_mp_mul (a, b, c);
044         }
045     }
046     c->sign = neg;
047     return res;
048 }

```

The implementation is rather simplistic and is not particularly noteworthy. Line 23 computes the sign of the result using the “?” operator from the C programming language. Line 40 computes δ using the fact that $1 \ll k$ is equal to 2^k .

5.3 Squaring

Squaring is a special case of multiplication where both multiplicands are equal. At first it may seem like there is no significant optimization available but in fact there is. Consider the multiplication of 576 against 241. In total there will be nine single precision multiplications performed which are $1 \cdot 6$, $1 \cdot 7$, $1 \cdot 5$, $4 \cdot 6$, $4 \cdot 7$, $4 \cdot 5$, $2 \cdot 6$, $2 \cdot 7$ and $2 \cdot 5$. Now consider the multiplication of 123 against 123. The nine products are $3 \cdot 3$, $3 \cdot 2$, $3 \cdot 1$, $2 \cdot 3$, $2 \cdot 2$, $2 \cdot 1$, $1 \cdot 3$, $1 \cdot 2$ and $1 \cdot 1$. On closer inspection some of the products are equivalent. For example, $3 \cdot 2 = 2 \cdot 3$ and $3 \cdot 1 = 1 \cdot 3$.

For any n -digit input, there are $\frac{(n^2+n)}{2}$ possible unique single precision multiplications required compared to the n^2 required for multiplication. The following

diagram gives an example of the operations required.

\times	1	2	3	
	1	2	3	
	$3 \cdot 1$	$3 \cdot 2$	$3 \cdot 3$	Row 0
	$2 \cdot 1$	$2 \cdot 2$	$2 \cdot 3$	Row 1
$1 \cdot 1$	$1 \cdot 2$	$1 \cdot 3$		Row 2

Figure 5.11: Squaring Optimization Diagram

Starting from zero and numbering the columns from right to left a very simple pattern becomes obvious. For the purposes of this discussion let x represent the number being squared. The first observation is that in row k the $2k$ 'th column of the product has a $(x_k)^2$ term in it.

The second observation is that every column j in row k where $j \neq 2k$ is part of a double product. Every non-square term of a column will appear twice hence the name “double product”. Every odd column is made up entirely of double products. In fact every column is made up of double products and at most one square (*see the exercise section*).

The third and final observation is that for row k the first unique non-square term, that is, one that hasn't already appeared in an earlier row, occurs at column $2k + 1$. For example, on row 1 of the previous squaring, column one is part of the double product with column one from row zero. Column two of row one is a square and column three is the first unique column.

5.3.1 The Baseline Squaring Algorithm

The baseline squaring algorithm is meant to be a catch-all squaring algorithm. It will handle any of the input sizes that the faster routines will not handle.

 Algorithm **s_mp_sqr**.

Input. mp_int a
Output. $b \leftarrow a^2$

1. Init a temporary mp_int of at least $2 \cdot a.used + 1$ digits. (*mp_init_size*)
 2. If step 1 failed return(*MP_MEM*)
 3. $t.used \leftarrow 2 \cdot a.used + 1$
 4. For ix from 0 to $a.used - 1$ do
 - Calculate the square.
 - 4.1 $\hat{r} \leftarrow t_{2ix} + (a_{ix})^2$
 - 4.2 $t_{2ix} \leftarrow \hat{r} \pmod{\beta}$
 - Calculate the double products after the square.
 - 4.3 $u \leftarrow \lfloor \hat{r}/\beta \rfloor$
 - 4.4 For iy from $ix + 1$ to $a.used - 1$ do
 - 4.4.1 $\hat{r} \leftarrow 2 \cdot a_{ix}a_{iy} + t_{ix+iy} + u$
 - 4.4.2 $t_{ix+iy} \leftarrow \hat{r} \pmod{\beta}$
 - 4.4.3 $u \leftarrow \lfloor \hat{r}/\beta \rfloor$
 - Set the last carry.
 - 4.5 While $u > 0$ do
 - 4.5.1 $iy \leftarrow iy + 1$
 - 4.5.2 $\hat{r} \leftarrow t_{ix+iy} + u$
 - 4.5.3 $t_{ix+iy} \leftarrow \hat{r} \pmod{\beta}$
 - 4.5.4 $u \leftarrow \lfloor \hat{r}/\beta \rfloor$
 5. Clamp excess digits of t . (*mp_clamp*)
 6. Exchange b and t .
 7. Clear t (*mp_clear*)
 8. Return(*MP_OKAY*)
-

Figure 5.12: Algorithm s_mp_sqr

Algorithm s_mp_sqr. This algorithm computes the square of an input using the three observations on squaring. It is based fairly faithfully on algorithm 14.16 of HAC [2, pp.596-597]. Similar to algorithm s_mp_mul_digs, a temporary mp_int is allocated to hold the result of the squaring. This allows the destination mp_int to be the same as the source mp_int.

The outer loop of this algorithm begins on step 4. It is best to think of the outer loop as walking down the rows of the partial results, while the inner loop computes the columns of the partial result. Step 4.1 and 4.2 compute the square term for each row, and step 4.3 and 4.4 propagate the carry and compute the double products.

The requirement that a `mp_word` be able to represent the range $0 \leq x < 2\beta^2$ arises from this very algorithm. The product $a_{ix}a_{iy}$ will lie in the range $0 \leq x \leq \beta^2 - 2\beta + 1$ which is obviously less than β^2 meaning that when it is multiplied by two, it can be properly represented by a `mp_word`.

Similar to algorithm `s_mp_mul_digs`, after every pass of the inner loop, the destination is correctly set to the sum of all of the partial results calculated so far. This involves expensive carry propagation which will be eliminated in the next algorithm.

File: `bn_s_mp_sqr.c`

```

016
017  /* low level squaring, b = a*a, HAC pp.596-597, Algorithm 14.16 */
018  int
019  s_mp_sqr (mp_int * a, mp_int * b)
020  {
021      mp_int t;
022      int res, ix, iy, pa;
023      mp_word r;
024      mp_digit u, tmpx, *tmpt;
025
026      pa = a->used;
027      if ((res = mp_init_size (&t, 2*pa + 1)) != MP_OKAY) {
028          return res;
029      }
030
031      /* default used is maximum possible size */
032      t.used = 2*pa + 1;
033
034      for (ix = 0; ix < pa; ix++) {
035          /* first calculate the digit at 2*ix */
036          /* calculate double precision result */
037          r = ((mp_word) t.dp[2*ix]) +
038              ((mp_word)a->dp[ix])*((mp_word)a->dp[ix]);
039
040          /* store lower part in result */
041          t.dp[ix+ix] = (mp_digit) (r & ((mp_word) MP_MASK));
042
043          /* get the carry */
044          u = (mp_digit)(r >> ((mp_word) DIGIT_BIT));
045
046          /* left hand side of A[ix] * A[iy] */
047          tmpx = a->dp[ix];

```

```

048
049     /* alias for where to store the results */
050     tmp      = t.dp + (2*ix + 1);
051
052     for (iy = ix + 1; iy < pa; iy++) {
053         /* first calculate the product */
054         r      = ((mp_word)tmpx) * ((mp_word)a->dp[iy]);
055
056         /* now calculate the double precision result, note we use
057          * addition instead of *2 since it's easier to optimize
058          */
059         r      = ((mp_word) *tmp) + r + r + ((mp_word) u);
060
061         /* store lower part */
062         *tmp++ = (mp_digit) (r & ((mp_word) MP_MASK));
063
064         /* get carry */
065         u      = (mp_digit)(r >> ((mp_word) DIGIT_BIT));
066     }
067     /* propagate upwards */
068     while (u != ((mp_digit) 0)) {
069         r      = ((mp_word) *tmp) + ((mp_word) u);
070         *tmp++ = (mp_digit) (r & ((mp_word) MP_MASK));
071         u      = (mp_digit)(r >> ((mp_word) DIGIT_BIT));
072     }
073 }
074
075 mp_clamp (&t);
076 mp_exch (&t, b);
077 mp_clear (&t);
078 return MP_OKAY;
079 }

```

Inside the outer loop (*see line 34*) the square term is calculated on line 37. Line 44 extracts the carry from the square term. Aliases for a_{ix} and t_{ix+iy} are initialized on lines 47 and 50 respectively. The doubling is performed using two additions (*see line 59*) since it is usually faster than shifting, if not at least as fast.

5.3.2 Faster Squaring by the “Comba” Method

A major drawback to the baseline method is the requirement for single precision shifting inside the $O(n^2)$ nested loop. Squaring has an additional drawback that it must double the product inside the inner loop as well. As for multiplication, the Comba technique can be used to eliminate these performance hazards.

The first obvious solution is to make an array of `mp_word`s which will hold all of the columns. This will indeed eliminate all of the carry propagation operations from the inner loop. However, the inner product must still be doubled $O(n^2)$ times. The solution stems from the simple fact that $2a + 2b + 2c = 2(a + b + c)$. That is the sum of all of the double products is equal to double the sum of all the products. For example, $ab + ba + ac + ca = 2ab + 2ac = 2(ab + ac)$.

However, we cannot simply double all of the columns, since the squares appear only once per row. The most practical solution is to have two `mp_word` arrays. One array will hold the squares and the other array will hold the double products. With both arrays the doubling and carry propagation can be moved to a $O(n)$ work level outside the $O(n^2)$ level.

Algorithm **fast_s_mp_sqr**.

Input. mp_int a

Output. $b \leftarrow a^2$

Place two arrays of **MP_WARRAY** mp_words named \hat{W} and \hat{X} on the stack.

1. If $b.alloc < 2a.used + 1$ then grow b to $2a.used + 1$ digits. (*mp_grow*).
2. If step 1 failed return(*MP_MEM*).
3. for ix from 0 to $2a.used + 1$ do
 - 3.1 $\hat{W}_{ix} \leftarrow 0$
 - 3.2 $\hat{X}_{ix} \leftarrow 0$
4. for ix from 0 to $a.used - 1$ do

Compute the square.

 - 4.1 $\hat{X}_{ix+ix} \leftarrow (a_{ix})^2$

Compute the double products.

 - 4.2 for iy from $ix + 1$ to $a.used - 1$ do
 - 4.2.1 $\hat{W}_{ix+iy} \leftarrow \hat{W}_{ix+iy} + a_{ix}a_{iy}$
5. $oldused \leftarrow b.used$
6. $b.used \leftarrow 2a.used + 1$

Double the products and propagate the carries simultaneously.

7. $\hat{W}_0 \leftarrow 2\hat{W}_0 + \hat{X}_0$
 8. for ix from 1 to $2a.used$ do
 - 8.1 $\hat{W}_{ix} \leftarrow 2\hat{W}_{ix} + \hat{X}_{ix}$
 - 8.2 $\hat{W}_{ix} \leftarrow \hat{W}_{ix} + \lceil \hat{W}_{ix-1} / \beta \rceil$
 - 8.3 $b_{ix-1} \leftarrow \hat{W}_{ix-1} \pmod{\beta}$
 9. $b_{2a.used} \leftarrow \hat{W}_{2a.used} \pmod{\beta}$
 10. if $2a.used + 1 < oldused$ then do
 - 10.1 for ix from $2a.used + 1$ to $oldused$ do
 - 10.1.1 $b_{ix} \leftarrow 0$
 11. Clamp excess digits from b . (*mp_clamp*)
 12. Return(*MP_OKAY*).
-

Figure 5.13: Algorithm fast_s_mp_sqr

Algorithm fast_s_mp_sqr. This algorithm computes the square of an input using the Comba technique. It is designed to be a replacement for algorithm `s_mp_sqr` when the number of input digits is less than **MP_WARRAY** and less than $\frac{\beta}{2}$.

This routine requires two arrays of mp_words to be placed on the stack. The

first array \hat{W} will hold the double products and the second array \hat{X} will hold the squares. Though only at most $\frac{MP_WARRAY}{2}$ words of \hat{X} are used, it has proven faster on most processors to simply make it a full size array.

The loop on step 3 will zero the two arrays to prepare them for the squaring step. Step 4.1 computes the squares of the product. Note how it simply assigns the value into the \hat{X} array. The nested loop on step 4.2 computes the doubles of the products. This loop computes the sum of the products for each column. They are not doubled until later.

After the squaring loop, the products stored in \hat{W} must be doubled and the carries propagated forwards. It makes sense to do both operations at the same time. The expression $\hat{W}_{ix} \leftarrow 2\hat{W}_{ix} + \hat{X}_{ix}$ computes the sum of the double product and the squares in place.

File: bn_fast_s_mp_sqr.c

```

016
017  /* fast squaring
018  *
019  * This is the comba method where the columns of the product
020  * are computed first then the carries are computed. This
021  * has the effect of making a very simple inner loop that
022  * is executed the most
023  *
024  * W2 represents the outer products and W the inner.
025  *
026  * A further optimizations is made because the inner
027  * products are of the form "A * B * 2". The *2 part does
028  * not need to be computed until the end which is good
029  * because 64-bit shifts are slow!
030  *
031  * Based on Algorithm 14.16 on pp.597 of HAC.
032  *
033  */
034  int
035  fast_s_mp_sqr (mp_int * a, mp_int * b)
036  {
037      int      olduse, newused, res, ix, pa;
038      mp_word W2[MP_WARRAY], W[MP_WARRAY];
039
040      /* calculate size of product and allocate as required */
041      pa = a->used;
042      newused = pa + pa + 1;
043      if (b->alloc < newused) {

```

```

044     if ((res = mp_grow (b, newused)) != MP_OKAY) {
045         return res;
046     }
047 }
048
049 /* zero temp buffer (columns)
050  * Note that there are two buffers.  Since squaring requires
051  * a outer and inner product and the inner product requires
052  * computing a product and doubling it (a relatively expensive
053  * op to perform n**2 times if you don't have to) the inner and
054  * outer products are computed in different buffers.  This way
055  * the inner product can be doubled using n doublings instead of
056  * n**2
057  */
058 memset (W, 0, newused * sizeof (mp_word));
059 memset (W2, 0, newused * sizeof (mp_word));
060
061 /* This computes the inner product.  To simplify the inner N**2 loop
062  * the multiplication by two is done afterwards in the N loop.
063  */
064 for (ix = 0; ix < pa; ix++) {
065     /* compute the outer product
066     *
067     * Note that every outer product is computed
068     * for a particular column only once which means that
069     * there is no need todo a double precision addition
070     * into the W2[] array.
071     */
072     W2[ix + ix] = ((mp_word)a->dp[ix]) * ((mp_word)a->dp[ix]);
073
074     {
075         register mp_digit tmpx, *tmpy;
076         register mp_word *_W;
077         register int iy;
078
079         /* copy of left side */
080         tmpx = a->dp[ix];
081
082         /* alias for right side */
083         tmpy = a->dp + (ix + 1);
084
085         /* the column to store the result in */

```

```

086     _W = W + (ix + ix + 1);
087
088     /* inner products */
089     for (iy = ix + 1; iy < pa; iy++) {
090         *_W++ += ((mp_word)tmpx) * ((mp_word)*tmpy++);
091     }
092 }
093 }
094
095 /* setup dest */
096 olduse = b->used;
097 b->used = newused;
098
099 /* now compute digits
100  *
101  * We have to double the inner product sums, add in the
102  * outer product sums, propagate carries and convert
103  * to single precision.
104  */
105 {
106     register mp_digit *tmpb;
107
108     /* double first value, since the inner products are
109     * half of what they should be
110     */
111     W[0] += W[0] + W2[0];
112
113     tmpb = b->dp;
114     for (ix = 1; ix < newused; ix++) {
115         /* double/add next digit */
116         W[ix] += W[ix] + W2[ix];
117
118         /* propagate carry forwards [from the previous digit] */
119         W[ix] = W[ix] + (W[ix - 1] >> ((mp_word) DIGIT_BIT));
120
121         /* store the current digit now that the carry isn't
122         * needed
123         */
124         *tmpb++ = (mp_digit) (W[ix - 1] & ((mp_word) MP_MASK));
125     }
126     /* set the last value. Note even if the carry is zero
127     * this is required since the next step will not zero

```

```

128     * it if b originally had a value at b->dp[2*a.used]
129     */
130     *tmpb++ = (mp_digit) (W[(newused) - 1] & ((mp_word) MP_MASK));
131
132     /* clear high digits of b if there were any originally */
133     for (; ix < olduse; ix++) {
134         *tmpb++ = 0;
135     }
136 }
137
138 mp_clamp (b);
139 return MP_OKAY;
140 }

```

– Write something deep and insightful later, Tom.

5.3.3 Polynomial Basis Squaring

The same algorithm that performs optimal polynomial basis multiplication can be used to perform polynomial basis squaring. The minor exception is that $\zeta_y = f(y)g(y)$ is actually equivalent to $\zeta_y = f(y)^2$ since $f(y) = g(y)$. Instead of performing $2n + 1$ multiplications to find the ζ relations, squaring operations are performed instead.

5.3.4 Karatsuba Squaring

Let $f(x) = ax + b$ represent the polynomial basis representation of a number to square. Let $h(x) = (f(x))^2$ represent the square of the polynomial. The Karatsuba equation can be modified to square a number with the following equation.

$$h(x) = a^2x^2 + (a^2 + b^2 - (a - b)^2)x + b^2 \quad (5.7)$$

Upon closer inspection this equation only requires the calculation of three half-sized squares: a^2 , b^2 and $(a - b)^2$. As in Karatsuba multiplication, this algorithm can be applied recursively on the input and will achieve an asymptotic running time of $O(n^{\lg(3)})$.

You might ask yourself, if the asymptotic time of Karatsuba squaring and multiplication is the same, why not simply use the multiplication algorithm instead? The answer to this arises from the cutoff point for squaring. As in multiplication there exists a cutoff point, at which the time required for a Comba

based squaring and a Karatsuba based squaring meet. Due to the overhead inherent in the Karatsuba method, the cutoff point is fairly high. For example, on an AMD Athlon XP processor with $\beta = 2^{28}$, the cutoff point is around 127 digits.

Consider squaring a 200 digit number with this technique. It will be split into two 100 digit halves which are subsequently squared. The 100 digit halves will not be squared using Karatsuba, but instead using the faster Comba based squaring algorithm. If Karatsuba multiplication were used instead, the 100 digit numbers would be squared with a slower Comba based multiplication.

Algorithm **mp_karatsuba_sqr**.

Input. mp_int a

Output. $b \leftarrow a^2$

1. Initialize the following temporary mp_ints: $x0, x1, t1, t2, x0x0$ and $x1x1$.
2. If any of the initializations on step 1 failed return(*MP_MEM*).

Split the input. e.g. $a = x1\beta^B + x0$

3. $B \leftarrow \lfloor a.used/2 \rfloor$
4. $x0 \leftarrow a \pmod{\beta^B}$ (*mp_mod_2d*)
5. $x1 \leftarrow \lfloor a/\beta^B \rfloor$ (*mp_lshd*)

Calculate the three squares.

6. $x0x0 \leftarrow x0^2$ (*mp_sqr*)
7. $x1x1 \leftarrow x1^2$
8. $t1 \leftarrow x1 - x0$ (*mp_sub*)
9. $t1 \leftarrow t1^2$

Compute the middle term.

10. $t2 \leftarrow x0x0 + x1x1$ (*s_mp_add*)
11. $t1 \leftarrow t2 - t1$

Compute final product.

12. $t1 \leftarrow t1\beta^B$ (*mp_lshd*)
 13. $x1x1 \leftarrow x1x1\beta^{2B}$
 14. $t1 \leftarrow t1 + x0x0$
 15. $b \leftarrow t1 + x1x1$
 16. Return(*MP_OKAY*).
-

Figure 5.14: Algorithm mp_karatsuba_sqr

Algorithm mp_karatsuba_sqr. This algorithm computes the square of an input a using the Karatsuba technique. This algorithm is very similar to the Karatsuba based multiplication algorithm with the exception that the three half-size multiplications have been replaced with three half-size squarings.

The radix point for squaring is simply placed exactly in the middle of the digits when the input has an odd number of digits, otherwise it is placed just below the middle. Step 3, 4 and 5 compute the two halves required using B as the radix point. The first two squares in steps 6 and 7 are rather straightforward while the last square is of a more compact form.

By expanding $(x1 - x0)^2$, the $x1^2$ and $x0^2$ terms in the middle disappear, that is $x1^2 + x0^2 - (x1 - x0)^2 = 2 \cdot x0 \cdot x1$. Now if $5n$ single precision additions and a squaring of n -digits is faster than multiplying two n -digit numbers and doubling then this method is faster. Assuming no further recursions occur, the difference can be estimated with the following inequality.

Let p represent the cost of a single precision addition and q the cost of a single precision multiplication both in terms of time⁵.

$$5pn + \frac{q(n^2 + n)}{2} \leq pn + qn^2 \quad (5.8)$$

For example, on an AMD Athlon XP processor $p = \frac{1}{3}$ and $q = 6$. This implies that the following inequality should hold.

$$\begin{aligned} \frac{5n}{3} + 3n^2 + 3n &< \frac{n}{3} + 6n^2 \\ \frac{5}{3} + 3n + 3 &< \frac{1}{3} + 6n \\ \frac{13}{9} &< n \end{aligned}$$

This results in a cutoff point around $n = 2$. As a consequence it is actually faster to compute the middle term the “long way” on processors where multiplication is substantially slower⁶ than simpler operations such as addition.

File: bn_mp_karatsuba_sqr.c

```

016
017 /* Karatsuba squaring, computes b = a*a using three
018 * half size squarings
019 *
020 * See comments of mp_karatsuba_mul for details. It
021 * is essentially the same algorithm but merely
022 * tuned to perform recursive squarings.
023 */
024 int
025 mp_karatsuba_sqr (mp_int * a, mp_int * b)
026 {
027     mp_int  x0, x1, t1, t2, x0x0, x1x1;
028     int      B, err;
029
030     err = MP_MEM;

```

⁵Or machine clock cycles.

⁶On the Athlon there is a 1:17 ratio between clock cycles for addition and multiplication. On the Intel P4 processor this ratio is 1:29 making this method even more beneficial. The only common exception is the ARMv4 processor which has a ratio of 1:7.


```
031
032     /* min # of digits */
033     B = a->used;
034
035     /* now divide in two */
036     B = B / 2;
037
038     /* init copy all the temps */
039     if (mp_init_size (&x0, B) != MP_OKAY)
040         goto ERR;
041     if (mp_init_size (&x1, a->used - B) != MP_OKAY)
042         goto X0;
043
044     /* init temps */
045     if (mp_init_size (&t1, a->used * 2) != MP_OKAY)
046         goto X1;
047     if (mp_init_size (&t2, a->used * 2) != MP_OKAY)
048         goto T1;
049     if (mp_init_size (&x0x0, B * 2) != MP_OKAY)
050         goto T2;
051     if (mp_init_size (&x1x1, (a->used - B) * 2) != MP_OKAY)
052         goto X0X0;
053
054     {
055         register int x;
056         register mp_digit *dst, *src;
057
058         src = a->dp;
059
060         /* now shift the digits */
061         dst = x0.dp;
062         for (x = 0; x < B; x++) {
063             *dst++ = *src++;
064         }
065
066         dst = x1.dp;
067         for (x = B; x < a->used; x++) {
068             *dst++ = *src++;
069         }
070     }
071
072     x0.used = B;
```

```

073     x1.used = a->used - B;
074
075     mp_clamp (&x0);
076
077     /* now calc the products x0*x0 and x1*x1 */
078     if (mp_sqr (&x0, &x0x0) != MP_OKAY)
079         goto X1X1;          /* x0x0 = x0*x0 */
080     if (mp_sqr (&x1, &x1x1) != MP_OKAY)
081         goto X1X1;          /* x1x1 = x1*x1 */
082
083     /* now calc (x1-x0)**2 */
084     if (mp_sub (&x1, &x0, &t1) != MP_OKAY)
085         goto X1X1;          /* t1 = x1 - x0 */
086     if (mp_sqr (&t1, &t1) != MP_OKAY)
087         goto X1X1;          /* t1 = (x1 - x0) * (x1 - x0) */
088
089     /* add x0y0 */
090     if (s_mp_add (&x0x0, &x1x1, &t2) != MP_OKAY)
091         goto X1X1;          /* t2 = x0x0 + x1x1 */
092     if (mp_sub (&t2, &t1, &t1) != MP_OKAY)
093         goto X1X1;          /* t1 = x0x0 + x1x1 - (x1-x0)*(x1-x0) */
094
095     /* shift by B */
096     if (mp_lshd (&t1, B) != MP_OKAY)
097         goto X1X1;          /* t1 = (x0x0 + x1x1 - (x1-x0)*(x1-x0))<<B */
098     if (mp_lshd (&x1x1, B * 2) != MP_OKAY)
099         goto X1X1;          /* x1x1 = x1x1 << 2*B */
100
101     if (mp_add (&x0x0, &t1, &t1) != MP_OKAY)
102         goto X1X1;          /* t1 = x0x0 + t1 */
103     if (mp_add (&t1, &x1x1, b) != MP_OKAY)
104         goto X1X1;          /* t1 = x0x0 + t1 + x1x1 */
105
106     err = MP_OKAY;
107
108     X1X1:mp_clear (&x1x1);
109     X0X0:mp_clear (&x0x0);
110     T2:mp_clear (&t2);
111     T1:mp_clear (&t1);
112     X1:mp_clear (&x1);
113     X0:mp_clear (&x0);
114     ERR:

```

```

115     return err;
116 }

```

This implementation is largely based on the implementation of algorithm `mp_karatsuba_mul`. It uses the same inline style to copy and shift the input into the two halves. The loop from line 54 to line 70 has been modified since only one input exists. The **used** count of both x_0 and x_1 is fixed up and x_0 is clamped before the calculations begin. At this point x_1 and x_0 are valid equivalents to the respective halves as if `mp_rshd` and `mp_mod_2d` had been used.

By inlining the copy and shift operations the cutoff point for Karatsuba multiplication can be lowered. On the Athlon the cutoff point is exactly at the point where Comba squaring can no longer be used (*128 digits*). On slower processors such as the Intel P4 it is actually below the Comba limit (*at 110 digits*).

This routine uses the same error trap coding style as `mp_karatsuba_sqr`. As the temporary variables are initialized errors are redirected to the error trap higher up. If the algorithm completes without error the error code is set to **MP_OKAY** and `mp_clears` are executed normally.

Last paragraph sucks. re-write! – Tom

5.3.5 Toom-Cook Squaring

The Toom-Cook squaring algorithm `mp_toom_sqr` is heavily based on the algorithm `mp_toom_mul` with the exception that squarings are used instead of multiplication to find the five relations.. The reader is encouraged to read the description of the latter algorithm and try to derive their own Toom-Cook squaring algorithm.

5.3.6 High Level Squaring

Algorithm **mp_sqr**.
Input. mp_int a
Output. $b \leftarrow a^2$

1. If $a.used \geq TOOM_SQR_CUTOFF$ then
 - 1.1 $b \leftarrow a^2$ using algorithm mp_toom_sqr
2. else if $a.used \geq KARATSUBA_SQR_CUTOFF$ then
 - 2.1 $b \leftarrow a^2$ using algorithm mp_karatsuba_sqr
3. else
 - 3.1 $digs \leftarrow a.used + b.used + 1$
 - 3.2 If $digs < MP_ARRAY$ and $a.used \leq \delta$ then
 - 3.2.1 $b \leftarrow a^2$ using algorithm fast_s_mp_sqr.
 - 3.3 else
 - 3.3.1 $b \leftarrow a^2$ using algorithm s_mp_sqr.
4. $b.sign \leftarrow MP_ZPOS$
5. Return the result of the unsigned squaring performed.

Figure 5.15: Algorithm mp_sqr

Algorithm mp_sqr. This algorithm computes the square of the input using one of four different algorithms. If the input is very large and has at least **TOOM_SQR_CUTOFF** or **KARATSUBA_SQR_CUTOFF** digits then either the Toom-Cook or the Karatsuba Squaring algorithm is used. If neither of the polynomial basis algorithms should be used then either the Comba or baseline algorithm is used.

File: bn_mp_sqr.c

```

016
017  /* computes b = a*a */
018  int
019  mp_sqr (mp_int * a, mp_int * b)
020  {
021      int    res;
022
023      /* use Toom-Cook? */
024      if (a->used >= TOOM_SQR_CUTOFF) {
025          res = mp_toom_sqr(a, b);
026          /* Karatsuba? */
027      } else if (a->used >= KARATSUBA_SQR_CUTOFF) {
028          res = mp_karatsuba_sqr (a, b);
029      } else {

```

```

030     /* can we use the fast comba multiplier? */
031     if ((a->used * 2 + 1) < MP_WARRAY &&
032         a->used <
033         (1 << (sizeof(mp_word) * CHAR_BIT - 2*DIGIT_BIT - 1))) {
034         res = fast_s_mp_sqr (a, b);
035     } else {
036         res = s_mp_sqr (a, b);
037     }
038 }
039 b->sign = MP_ZPOS;
040 return res;
041 }

```

Exercises

- [3] Devise an efficient algorithm for selection of the radix point to handle inputs that have different number of digits in Karatsuba multiplication.
- [3] In section 5.3 the fact that every column of a squaring is made up of double products and at most one square is stated. Prove this statement.
- [2] In the Comba squaring algorithm half of the \hat{X} variables are not used. Revise algorithm `fast_s_mp_sqr` to shrink the \hat{X} array.
- [3] Prove the equation for Karatsuba squaring.
- [1] Prove that Karatsuba squaring requires $O(n^{\lg(3)})$ time.
- [2] Determine the minimal ratio between addition and multiplication clock cycles required for equation 6.7 to be true.

Chapter 6

Modular Reduction

6.1 Basics of Modular Reduction

Modular reduction is an operation that arises quite often within public key cryptography algorithms and various number theoretic algorithms, such as factoring. Modular reduction algorithms are the third class of algorithms of the “multipliers” set. A number a is said to be *reduced* modulo another number b by finding the remainder of the division a/b . Full integer division with remainder is a topic to be covered in 8.1.

Modular reduction is equivalent to solving for r in the following equation. $a = bq + r$ where $q = \lfloor a/b \rfloor$. The result r is said to be “congruent to a modulo b ” which is also written as $r \equiv a \pmod{b}$. In other vernacular r is known as the “modular residue” which leads to “quadratic residue”¹ and other forms of residues.

Modular reductions are normally used to create either finite groups, rings or fields. The most common usage for performance driven modular reductions is in modular exponentiation algorithms. That is to compute $d = a^b \pmod{c}$ as fast as possible. This operation is used in the RSA and Diffie-Hellman public key algorithms, for example. Modular multiplication and squaring also appears as a fundamental operation in Elliptic Curve cryptographic algorithms. As will be discussed in the subsequent chapter there exist fast algorithms for computing modular exponentiations without having to perform (*in this example*) $b - 1$ multiplications. These algorithms will produce partial results in the

¹That’s fancy talk for $b \equiv a^2 \pmod{p}$.

range $0 \leq x < c^2$ which can be taken advantage of to create several efficient algorithms. They have also been used to create redundancy check algorithms known as CRCs, error correction codes such as Reed-Solomon and solve a variety of number theoretic problems.

6.2 The Barrett Reduction

The Barrett reduction algorithm [7] was inspired by fast division algorithms which multiply by the reciprocal to emulate division. Barretts observation was that the residue c of a modulo b is equal to

$$c = a - b \cdot \lfloor a/b \rfloor \quad (6.1)$$

Since algorithms such as modular exponentiation would be using the same modulus extensively, typical DSP² intuition would indicate the next step would be to replace a/b by a multiplication by the reciprocal. However, DSP intuition on its own will not work as these numbers are considerably larger than the precision of common DSP floating point data types. It would take another common optimization to optimize the algorithm.

6.2.1 Fixed Point Arithmetic

The trick used to optimize the above equation is based on a technique of emulating floating point data types with fixed precision integers. Fixed point arithmetic would become very popular as it greatly optimize the “3d-shooter” genre of games in the mid 1990s when floating point units were fairly slow if not unavailable. The idea behind fixed point arithmetic is to take a normal k -bit integer data type and break it into p -bit integer and a q -bit fraction part (*where* $p + q = k$).

In this system a k -bit integer n would actually represent $n/2^q$. For example, with $q = 4$ the integer $n = 37$ would actually represent the value 2.3125. To multiply two fixed point numbers the integers are multiplied using traditional arithmetic and subsequently normalized by moving the implied decimal point back to where it should be. For example, with $q = 4$ to multiply the integers 9 and 5 they must be converted to fixed point first by multiplying by 2^q . Let $a = 9(2^q)$ represent the fixed point representation of 9 and $b = 5(2^q)$ represent

²It is worth noting that Barrett’s paper targeted the DSP56K processor.

the fixed point representation of 5. The product ab is equal to $45(2^{2q})$ which when normalized by dividing by 2^q produces $45(2^q)$.

This technique became popular since a normal integer multiplication and logical shift right are the only required operations to perform a multiplication of two fixed point numbers. Using fixed point arithmetic, division can be easily approximated by multiplying by the reciprocal. If 2^q is equivalent to one then $2^q/b$ is equivalent to the fixed point approximation of $1/b$ using real arithmetic. Using this fact dividing an integer a by another integer b can be achieved with the following expression.

$$\lfloor a/b \rfloor \sim \lfloor (a \cdot \lfloor 2^q/b \rfloor) / 2^q \rfloor \quad (6.2)$$

The precision of the division is proportional to the value of q . If the divisor b is used frequently as is the case with modular exponentiation pre-computing $2^q/b$ will allow a division to be performed with a multiplication and a right shift. Both operations are considerably faster than division on most processors.

Consider dividing 19 by 5. The correct result is $\lfloor 19/5 \rfloor = 3$. With $q = 3$ the reciprocal is $\lfloor 2^3/5 \rfloor = 1$ which leads to a product of 19 which when divided by 2^3 produces 2. However, with $q = 4$ the reciprocal is $\lfloor 2^4/5 \rfloor = 3$ and the result of the emulated division is $\lfloor 3 \cdot 19/2^4 \rfloor = 3$ which is correct. The value of 2^q must be close to or ideally larger than the dividend. In effect if a is the dividend then q should allow $0 \leq \lfloor a/2^q \rfloor \leq 1$ in order for this approach to work correctly. Plugging this form of division into the original equation the following modular residue equation arises.

$$c = a - b \cdot \lfloor (a \cdot \lfloor 2^q/b \rfloor) / 2^q \rfloor \quad (6.3)$$

Using the notation from [7] the value of $\lfloor 2^q/b \rfloor$ will be represented by the μ symbol. Using the μ variable also helps re-inforce the idea that it is meant to be computed once and re-used.

$$c = a - b \cdot \lfloor (a \cdot \mu) / 2^q \rfloor \quad (6.4)$$

Provided that $2^q \geq a$ this algorithm will produce a quotient that is either exactly correct or off by a value of one. In the context of Barrett reduction the value of a is bound by $0 \leq a \leq (b-1)^2$ meaning that $2^q \geq b^2$ is sufficient to ensure the reciprocal will have enough precision.

Let n represent the number of digits in b . This algorithm requires approximately $2n^2$ single precision multiplications to produce the quotient and another n^2 single precision multiplications to find the residue. In total $3n^2$ single precision multiplications are required to reduce the number.

For example, if $b = 1179677$ and $q = 41$ ($2^q > b^2$), then the reciprocal μ is equal to $\lfloor 2^q/b \rfloor = 1864089$. Consider reducing $a = 180388626447$ modulo b using the above reduction equation. The quotient using the new formula is $\lfloor (a \cdot \mu)/2^q \rfloor = 152913$. By subtracting $152913b$ from a the correct residue $a \equiv 677346 \pmod{b}$ is found.

6.2.2 Choosing a Radix Point

Using the fixed point representation a modular reduction can be performed with $3n^2$ single precision multiplications. If that were the best that could be achieved a full division³ might as well be used in its place. The key to optimizing the reduction is to reduce the precision of the initial multiplication that finds the quotient.

Let a represent the number of which the residue is sought. Let b represent the modulus used to find the residue. Let m represent the number of digits in b . For the purposes of this discussion we will assume that the number of digits in a is $2m$, which is generally true if two m -digit numbers have been multiplied. Dividing a by b is the same as dividing a $2m$ digit integer by a m digit integer. Digits below the $m - 1$ 'th digit of a will contribute at most a value of 1 to the quotient because $\beta^k < b$ for any $0 \leq k \leq m - 1$. Another way to express this is by re-writing a as two parts. If $a' \equiv a \pmod{b^m}$ and $a'' = a - a'$ then $\frac{a}{b} \equiv \frac{a' + a''}{b}$ which is equivalent to $\frac{a'}{b} + \frac{a''}{b}$. Since a' is bound to be less than b the quotient is bound by $0 \leq \frac{a'}{b} < 1$.

Since the digits of a' do not contribute much to the quotient the observation is that they might as well be zero. However, if the digits “might as well be zero” they might as well not be there in the first place. Let $q_0 = \lfloor a/\beta^{m-1} \rfloor$ represent the input with the irrelevant digits trimmed. Now the modular reduction is trimmed to the almost equivalent equation

$$c = a - b \cdot \lfloor (q_0 \cdot \mu)/\beta^{m+1} \rfloor \quad (6.5)$$

Note that the original divisor 2^q has been replaced with β^{m+1} where in this case q is a multiple of $lg(\beta)$. Also note that the exponent on the divisor when added to the amount q_0 was shifted by equals $2m$. If the optimization had not been performed the divisor would have the exponent $2m$ so in the end the exponents do “add up”. Using the above equation the quotient $\lfloor (q_0 \cdot \mu)/\beta^{m+1} \rfloor$ can be off from the true quotient by at most two. The original fixed point

³A division requires approximately $O(2cn^2)$ single precision multiplications for a small value of c . See 8.1 for further details.

quotient can be off by as much as one (*provided the radix point is chosen suitably*) and now that the lower irrelevant digits have been trimmed the quotient can be off by an additional value of one for a total of at most two. This implies that $0 \leq a - b \cdot \lfloor (q_0 \cdot \mu) / \beta^{m+1} \rfloor < 3b$. By first subtracting b times the quotient and then conditionally subtracting b once or twice the residue is found.

The quotient is now found using $(m+1)(m) = m^2 + m$ single precision multiplications and the residue with an additional m^2 single precision multiplications, ignoring the subtractions required. In total $2m^2 + m$ single precision multiplications are required to find the residue. This is considerably faster than the original attempt.

For example, let $\beta = 10$ represent the radix of the digits. Let $b = 9999$ represent the modulus which implies $m = 4$. Let $a = 99929878$ represent the value of which the residue is desired. In this case $q = 8$ since $10^7 < 9999^2$ meaning that $\mu = \lfloor \beta^q / b \rfloor = 10001$. With the new observation the multiplicand for the quotient is equal to $q_0 = \lfloor a / \beta^{m-1} \rfloor = 99929$. The quotient is then $\lfloor (q_0 \cdot \mu) / \beta^{m+1} \rfloor = 9993$. Subtracting $9993b$ from a and the correct residue $a \equiv 9871 \pmod{b}$ is found.

6.2.3 Trimming the Quotient

So far the reduction algorithm has been optimized from $3m^2$ single precision multiplications down to $2m^2 + m$ single precision multiplications. As it stands now the algorithm is already fairly fast compared to a full integer division algorithm. However, there is still room for optimization.

After the first multiplication inside the quotient ($q_0 \cdot \mu$) the value is shifted right by $m+1$ places effectively nullifying the lower half of the product. It would be nice to be able to remove those digits from the product to effectively cut down the number of single precision multiplications. If the number of digits in the modulus m is far less than β a full product is not required for the algorithm to work properly. In fact the lower $m-2$ digits will not affect the upper half of the product at all and do not need to be computed.

The value of μ is a m -digit number and q_0 is a $m+1$ digit number. Using a full multiplier $(m+1)(m) = m^2 + m$ single precision multiplications would be required. Using a multiplier that will only produce digits at and above the $m-1$ 'th digit reduces the number of single precision multiplications to $\frac{m^2+m}{2}$ single precision multiplications.

6.2.4 Trimming the Residue

After the quotient has been calculated it is used to reduce the input. As previously noted the algorithm is not exact and it can be off by a small multiple of the modulus, that is $0 \leq a - b \cdot \lfloor (q_0 \cdot \mu) / \beta^{m+1} \rfloor < 3b$. If b is m digits then the result of reduction equation is a value of at most $m + 1$ digits (*provided* $3 < \beta$) implying that the upper $m - 1$ digits are implicitly zero.

The next optimization arises from this very fact. Instead of computing $b \cdot \lfloor (q_0 \cdot \mu) / \beta^{m+1} \rfloor$ using a full $O(m^2)$ multiplication algorithm only the lower $m + 1$ digits of the product have to be computed. Similarly the value of a can be reduced modulo β^{m+1} before the multiple of b is subtracted which simplifies the subtraction as well. A multiplication that produces only the lower $m + 1$ digits requires $\frac{m^2 + 3m - 2}{2}$ single precision multiplications.

With both optimizations in place the algorithm is the algorithm Barrett proposed. It requires $m^2 + 2m - 1$ single precision multiplications which is considerably faster than the straightforward $3m^2$ method.

6.2.5 The Barrett Algorithm

Algorithm **mp_reduce**.

Input. mp_int a , mp_int b and $\mu = \lfloor \beta^{2m}/b \rfloor$, $m = \lceil \lg_\beta(b) \rceil$, ($0 \leq a < b^2$, $b > 1$)

Output. $a \pmod{b}$

Let m represent the number of digits in b .

1. Make a copy of a and store it in q . (*mp_init_copy*)
2. $q \leftarrow \lfloor q/\beta^{m-1} \rfloor$ (*mp_rshd*)

Produce the quotient.

3. $q \leftarrow q \cdot \mu$ (*note: only produce digits at or above $m - 1$*)
4. $q \leftarrow \lfloor q/\beta^{m+1} \rfloor$

Subtract the multiple of modulus from the input.

5. $a \leftarrow a \pmod{\beta^{m+1}}$ (*mp_mod_2d*)
6. $q \leftarrow q \cdot b \pmod{\beta^{m+1}}$ (*s_mp_mul_digs*)
7. $a \leftarrow a - q$ (*mp_sub*)

Add β^{m+1} if a carry occurred.

8. If $a < 0$ then (*mp_cmp_d*)
 - 8.1 $q \leftarrow 1$ (*mp_set*)
 - 8.2 $q \leftarrow q \cdot \beta^{m+1}$ (*mp_lshd*)
 - 8.3 $a \leftarrow a + q$

Now subtract the modulus if the residue is too large (e.g. quotient too small).

9. While $a \geq b$ do (*mp_cmp*)
 - 9.1 $c \leftarrow a - b$
 10. Clear q .
 11. Return(*MP_OKAY*)
-

Figure 6.1: Algorithm mp_reduce

Algorithm mp_reduce. This algorithm will reduce the input a modulo b in place using the Barrett algorithm. It is loosely based on algorithm 14.42 of HAC [2, pp. 602] which is based on the paper from Paul Barrett [7]. The algorithm has several restrictions and assumptions which must be adhered to for the algorithm to work.

First the modulus b is assumed to be positive and greater than one. If the modulus were less than or equal to one then subtracting a multiple of it would either accomplish nothing or actually enlarge the input. The input a must be in the range $0 \leq a < b^2$ in order for the quotient to have enough precision. If a

is the product of two numbers that were already reduced modulo b , this will not be a problem. Technically the algorithm will still work if $a \geq b^2$ but it will take much longer to finish. The value of μ is passed as an argument to this algorithm and is assumed to be calculated and stored before the algorithm is used.

Recall that the multiplication for the quotient on step 3 must only produce digits at or above the $m-1$ 'th position. An algorithm called *s_mp_mul_high_digs* which has not been presented is used to accomplish this task. The algorithm is based on *s_mp_mul_digs* except that instead of stopping at a given level of precision it starts at a given level of precision. This optimal algorithm can only be used if the number of digits in b is very much smaller than β .

While it is known that $a \geq b \cdot \lfloor (q_0 \cdot \mu) / \beta^{m+1} \rfloor$ only the lower $m+1$ digits are being used to compute the residue, so an implied "borrow" from the higher digits might leave a negative result. After the multiple of the modulus has been subtracted from a the residue must be fixed up in case it is negative. The invariant β^{m+1} must be added to the residue to make it positive again.

The while loop at step 9 will subtract b until the residue is less than b . If the algorithm is performed correctly this step is performed at most twice, and on average once. However, if $a \geq b^2$ than it will iterate substantially more times than it should.

File: bn_mp_reduce.c

```

016
017  /* reduces x mod m, assumes 0 < x < m**2, mu is
018   * precomputed via mp_reduce_setup.
019   * From HAC pp.604 Algorithm 14.42
020   */
021  int
022  mp_reduce (mp_int * x, mp_int * m, mp_int * mu)
023  {
024      mp_int  q;
025      int     res, um = m->used;
026
027      /* q = x */
028      if ((res = mp_init_copy (&q, x)) != MP_OKAY) {
029          return res;
030      }
031
032      /* q1 = x / b**(k-1) */
033      mp_rshd (&q, um - 1);
034
035      /* according to HAC this optimization is ok */

```

```
036     if (((unsigned long) um) > (((mp_digit)1) << (DIGIT_BIT - 1))) {
037         if ((res = mp_mul (&q, mu, &q)) != MP_OKAY) {
038             goto CLEANUP;
039         }
040     } else {
041         if ((res = s_mp_mul_high_digs (&q, mu, &q, um - 1)) != MP_OKAY) {
042             goto CLEANUP;
043         }
044     }
045
046     /* q3 = q2 / b**(k+1) */
047     mp_rshd (&q, um + 1);
048
049     /* x = x mod b**(k+1), quick (no division) */
050     if ((res = mp_mod_2d (x, DIGIT_BIT * (um + 1), x)) != MP_OKAY) {
051         goto CLEANUP;
052     }
053
054     /* q = q * m mod b**(k+1), quick (no division) */
055     if ((res = s_mp_mul_digs (&q, m, &q, um + 1)) != MP_OKAY) {
056         goto CLEANUP;
057     }
058
059     /* x = x - q */
060     if ((res = mp_sub (x, &q, x)) != MP_OKAY) {
061         goto CLEANUP;
062     }
063
064     /* If x < 0, add b**(k+1) to it */
065     if (mp_cmp_d (x, 0) == MP_LT) {
066         mp_set (&q, 1);
067         if ((res = mp_lshd (&q, um + 1)) != MP_OKAY)
068             goto CLEANUP;
069         if ((res = mp_add (x, &q, x)) != MP_OKAY)
070             goto CLEANUP;
071     }
072
073     /* Back off if it's too big */
074     while (mp_cmp (x, m) != MP_LT) {
075         if ((res = s_mp_sub (x, m, x)) != MP_OKAY) {
076             goto CLEANUP;
077         }

```

```

078     }
079
080     CLEANUP:
081         mp_clear (&q);
082
083         return res;
084     }

```

The first multiplication that determines the quotient can be performed by only producing the digits from $m - 1$ and up. This essentially halves the number of single precision multiplications required. However, the optimization is only safe if β is much larger than the number of digits in the modulus. In the source code this is evaluated on lines 36 to 44 where algorithm `s_mp_mul_high_digs` is used when it is safe to do so.

6.2.6 The Barrett Setup Algorithm

In order to use algorithm `mp_reduce` the value of μ must be calculated in advance. Ideally this value should be computed once and stored for future use so that the Barrett algorithm can be used without delay.

Algorithm **mp_reduce_setup**.
Input. mp_int a ($a > 1$)
Output. $\mu \leftarrow \lfloor \beta^{2m} / a \rfloor$

1. $\mu \leftarrow 2^{2 \cdot \lg(\beta) \cdot m}$ (*mp_2expt*)
2. $\mu \leftarrow \lfloor \mu / b \rfloor$ (*mp_div*)
3. Return(*MP_OKAY*)

Figure 6.2: Algorithm `mp_reduce_setup`

Algorithm `mp_reduce_setup`. This algorithm computes the reciprocal μ required for Barrett reduction. First β^{2m} is calculated as $2^{2 \cdot \lg(\beta) \cdot m}$ which is equivalent and much faster. The final value is computed by taking the integer quotient of $\lfloor \mu / b \rfloor$.

```

File: bn_mp_reduce_setup.c
016
017     /* pre-calculate the value required for Barrett reduction
018        * For a given modulus "b" it calculates the value required in "a"
019        */

```



```

020  int
021  mp_reduce_setup (mp_int * a, mp_int * b)
022  {
023      int    res;
024
025      if ((res = mp_2expt (a, b->used * 2 * DIGIT_BIT)) != MP_OKAY) {
026          return res;
027      }
028      return mp_div (a, b, a, NULL);
029  }

```

This simple routine calculates the reciprocal μ required by Barrett reduction. Note the extended usage of algorithm `mp_div` where the variable which would received the remainder is passed as `NULL`. As will be discussed in 8.1 the division routine allows both the quotient and the remainder to be passed as `NULL` meaning to ignore the value.

6.3 The Montgomery Reduction

Montgomery reduction⁴ [8] is by far the most interesting form of reduction in common use. It computes a modular residue which is not actually equal to the residue of the input yet instead equal to a residue times a constant. However, as perplexing as this may sound the algorithm is relatively simple and very efficient.

Throughout this entire section the variable n will represent the modulus used to form the residue. As will be discussed shortly the value of n must be odd. The variable x will represent the quantity of which the residue is sought. Similar to the Barrett algorithm the input is restricted to $0 \leq x < n^2$. To begin the description some simple number theory facts must be established.

Fact 1. Adding n to x does not change the residue since in effect it adds one to the quotient $\lfloor x/n \rfloor$. Another way to explain this is that n is (*or multiples of n are*) congruent to zero modulo n . Adding zero will not change the value of the residue.

Fact 2. If x is even then performing a division by two in \mathbb{Z} is congruent to $x \cdot 2^{-1} \pmod{n}$. Actually this is an application of the fact that if x is evenly divisible by any $k \in \mathbb{Z}$ then division in \mathbb{Z} will be congruent to multiplication by k^{-1} modulo n .

From these two simple facts the following simple algorithm can be derived.

⁴Thanks to Niels Ferguson for his insightful explanation of the algorithm.

Algorithm Montgomery Reduction.
Input. Integer x , n and k
Output. $2^{-k}x \pmod{n}$

1. for t from 1 to k do
 - 1.1 If x is odd then
 - 1.1.1 $x \leftarrow x + n$
 - 1.2 $x \leftarrow x/2$
2. Return x .

Figure 6.3: Algorithm Montgomery Reduction

The algorithm reduces the input one bit at a time using the two congruencies stated previously. Inside the loop n , which is odd, is added to x if x is odd. This forces x to be even which allows the division by two in \mathbb{Z} to be congruent to a modular division by two. Since x is assumed to be initially much larger than n the addition of n will contribute an insignificant magnitude to x . Let r represent the final result of the Montgomery algorithm. If $k > \lg(n)$ and $0 \leq x < n^2$ then the final result is limited to $0 \leq r < \lfloor x/2^k \rfloor + n$. As a result at most a single subtraction is required to get the residue desired.

Step number (t)	Result (x)
1	$x + n = 5812, x/2 = 2906$
2	$x/2 = 1453$
3	$x + n = 1710, x/2 = 855$
4	$x + n = 1112, x/2 = 556$
5	$x/2 = 278$
6	$x/2 = 139$
7	$x + n = 396, x/2 = 198$
8	$x/2 = 99$

Figure 6.4: Example of Montgomery Reduction (I)

Consider the example in figure 6.4 which reduces $x = 5555$ modulo $n = 257$ when $k = 8$. The result of the algorithm $r = 99$ is congruent to the value of $2^{-8} \cdot 5555 \pmod{257}$. When r is multiplied by 2^8 modulo 257 the correct residue $r \equiv 158$ is produced.

Let $k = \lfloor \lg(n) \rfloor + 1$ represent the number of bits in n . The current algorithm requires $2k^2$ single precision shifts and k^2 single precision additions. At this rate

the algorithm is most certainly slower than Barrett reduction and not terribly useful. Fortunately there exists an alternative representation of the algorithm.

Algorithm **Montgomery Reduction** (modified I).
Input. Integer x , n and k
Output. $2^{-k}x \pmod{n}$

1. for t from 0 to $k - 1$ do
 - 1.1 If the t 'th bit of x is one then
 - 1.1.1 $x \leftarrow x + 2^t n$
2. Return $x/2^k$.

Figure 6.5: Algorithm Montgomery Reduction (modified I)

This algorithm is equivalent since $2^t n$ is a multiple of n and the lower k bits of x are zero by step 2. The number of single precision shifts has now been reduced from $2k^2$ to $k^2 + k$ which is only a small improvement.

Step number (t)	Result (x)	Result (x) in Binary
–	5555	1010110110011
1	$x + 2^0 n = 5812$	1011010110100
2	5812	1011010110100
3	$x + 2^2 n = 6840$	1101010111000
4	$x + 2^3 n = 8896$	10001011000000
5	8896	10001011000000
6	8896	10001011000000
7	$x + 2^6 n = 25344$	110001100000000
8	25344	110001100000000
–	$x/2^k = 99$	

Figure 6.6: Example of Montgomery Reduction (II)

Figure 6.6 demonstrates the modified algorithm reducing $x = 5555$ modulo $n = 257$ with $k = 8$. With this algorithm a single shift right at the end is the only right shift required to reduce the input instead of k right shifts inside the loop. Note that for the iterations $t = 2, 5, 6$ and 8 where the result x is not changed. In those iterations the t 'th bit of x is zero and the appropriate multiple of n does not need to be added to force the t 'th bit of the result to zero.

6.3.1 Digit Based Montgomery Reduction

Instead of computing the reduction on a bit-by-bit basis it is actually much faster to compute it on digit-by-digit basis. Consider the previous algorithm re-written to compute the Montgomery reduction in this new fashion.

Algorithm **Montgomery Reduction** (modified II).
Input. Integer x , n and k
Output. $\beta^{-k}x \pmod{n}$

1. for t from 0 to $k - 1$ do
 - 1.1 $x \leftarrow x + \mu n \beta^t$
2. Return x/β^k .

Figure 6.7: Algorithm Montgomery Reduction (modified II)

The value $\mu n \beta^t$ is a multiple of the modulus n meaning that it will not change the residue. If the first digit of the value $\mu n \beta^t$ equals the negative (modulo β) of the t 'th digit of x then the addition will result in a zero digit. This problem breaks down to solving the following congruency.

$$\begin{aligned} x_t + \mu n_0 &\equiv 0 \pmod{\beta} \\ \mu n_0 &\equiv -x_t \pmod{\beta} \\ \mu &\equiv -x_t/n_0 \pmod{\beta} \end{aligned}$$

In each iteration of the loop on step 1 a new value of μ must be calculated. The value of $-1/n_0 \pmod{\beta}$ is used extensively in this algorithm and should be precomputed. Let ρ represent the negative of the modular inverse of n_0 modulo β .

For example, let $\beta = 10$ represent the radix. Let $n = 17$ represent the modulus which implies $k = 2$ and $\rho \equiv 7$. Let $x = 33$ represent the value to reduce.

Step (t)	Value of x	Value of μ
–	33	–
0	$33 + \mu n = 50$	1
1	$50 + \mu n \beta = 900$	5

Figure 6.8: Example of Montgomery Reduction

The final result 900 is then divided by β^k to produce the final result 9. The first observation is that $9 \not\equiv x \pmod{n}$ which implies the result is not the modular residue of x modulo n . However, recall that the residue is actually multiplied by β^{-k} in the algorithm. To get the true residue the value must be multiplied by β^k . In this case $\beta^k \equiv 15 \pmod{n}$ and the correct residue is $9 \cdot 15 \equiv 16 \pmod{n}$.

6.3.2 Baseline Montgomery Reduction

The baseline Montgomery reduction algorithm will produce the residue for any size input. It is designed to be a catch-all algorithm for Montgomery reductions.

Algorithm mp_montgomery_reduce.

Input. mp_int x , mp_int n and a digit $\rho \equiv -1/n_0 \pmod{n}$.
 $(0 \leq x < n^2, n > 1, (n, \beta) = 1, \beta^k > n)$

Output. $\beta^{-k}x \pmod{n}$

1. $digs \leftarrow 2n.used + 1$
2. If $digs < MP_ARRAY$ and $m.used < \delta$ then
 - 2.1 Use algorithm fast_mp_montgomery_reduce instead.

Setup x for the reduction.

3. If $x.alloc < digs$ then grow x to $digs$ digits.
4. $x.used \leftarrow digs$

Eliminate the lower k digits.

5. For ix from 0 to $k - 1$ do
 - 5.1 $\mu \leftarrow x_{ix} \cdot \rho \pmod{\beta}$
 - 5.2 $u \leftarrow 0$
 - 5.3 For iy from 0 to $k - 1$ do
 - 5.3.1 $\hat{r} \leftarrow \mu n_{iy} + x_{ix+iy} + u$
 - 5.3.2 $x_{ix+iy} \leftarrow \hat{r} \pmod{\beta}$
 - 5.3.3 $u \leftarrow \lfloor \hat{r}/\beta \rfloor$
 - 5.4 While $u > 0$ do
 - 5.4.1 $iy \leftarrow iy + 1$
 - 5.4.2 $x_{ix+iy} \leftarrow x_{ix+iy} + u$
 - 5.4.3 $u \leftarrow \lfloor x_{ix+iy}/\beta \rfloor$
 - 5.4.4 $x_{ix+iy} \leftarrow x_{ix+iy} \pmod{\beta}$

Divide by β^k and fix up as required.

6. $x \leftarrow \lfloor x/\beta^k \rfloor$
 7. If $x \geq n$ then
 - 7.1 $x \leftarrow x - n$
 8. Return(MP_OKAY).
-

Figure 6.9: Algorithm mp_montgomery_reduce

Algorithm mp_montgomery_reduce. This algorithm reduces the input x modulo n in place using the Montgomery reduction algorithm. The algorithm is loosely based on algorithm 14.32 of [2, pp.601] except it merges the multiplication of $\mu n \beta^t$ with the addition in the inner loop. The restrictions on this algorithm are fairly easy to adapt to. First $0 \leq x < n^2$ bounds the input to

numbers in the same range as for the Barrett algorithm. Additionally if $n > 1$ and n is odd there will exist a modular inverse ρ . ρ must be calculated in advance of this algorithm. Finally the variable k is fixed and a pseudonym for $n.used$.

Step 2 decides whether a faster Montgomery algorithm can be used. It is based on the Comba technique meaning that there are limits on the size of the input. This algorithm is discussed in sub-section 6.3.3.

Step 5 is the main reduction loop of the algorithm. The value of μ is calculated once per iteration in the outer loop. The inner loop calculates $x + \mu n \beta^{ix}$ by multiplying μn and adding the result to x shifted by ix digits. Both the addition and multiplication are performed in the same loop to save time and memory. Step 5.4 will handle any additional carries that escape the inner loop.

Using a quick inspection this algorithm requires n single precision multiplications for the outer loop and n^2 single precision multiplications in the inner loop. In total $n^2 + n$ single precision multiplications which compares favourably to Barrett at $n^2 + 2n - 1$ single precision multiplications.

File: bn_mp_montgomery_reduce.c

```

016
017  /* computes xR**-1 == x (mod N) via Montgomery Reduction */
018  int
019  mp_montgomery_reduce (mp_int * x, mp_int * n, mp_digit rho)
020  {
021      int      ix, res, digs;
022      mp_digit mu;
023
024      /* can the fast reduction [comba] method be used?
025       *
026       * Note that unlike in mp_mul you're safely allowed *less*
027       * than the available columns [255 per default] since carries
028       * are fixed up in the inner loop.
029       */
030      digs = n->used * 2 + 1;
031      if ((digs < MP_WARRAY) &&
032          n->used <
033          (1 << ((CHAR_BIT * sizeof (mp_word)) - (2 * DIGIT_BIT)))) {
034          return fast_mp_montgomery_reduce (x, n, rho);
035      }
036
037      /* grow the input as required */
038      if (x->alloc < digs) {

```

```

039     if ((res = mp_grow (x, digs)) != MP_OKAY) {
040         return res;
041     }
042 }
043 x->used = digs;
044
045 for (ix = 0; ix < n->used; ix++) {
046     /* mu = ai * rho mod b
047     *
048     * The value of rho must be precalculated via
049     * bn_mp_montgomery_setup() such that
050     * it equals -1/n0 mod b this allows the
051     * following inner loop to reduce the
052     * input one digit at a time
053     */
054     mu = (mp_digit) (((mp_word)x->dp[ix]) * ((mp_word)rho) & MP_MASK);
055
056     /* a = a + mu * m * b**i */
057     {
058         register int iy;
059         register mp_digit *tmpn, *tmpx, u;
060         register mp_word r;
061
062         /* alias for digits of the modulus */
063         tmpn = n->dp;
064
065         /* alias for the digits of x [the input] */
066         tmpx = x->dp + ix;
067
068         /* set the carry to zero */
069         u = 0;
070
071         /* Multiply and add in place */
072         for (iy = 0; iy < n->used; iy++) {
073             /* compute product and sum */
074             r          = ((mp_word)mu) * ((mp_word)*tmpn++) +
075                 ((mp_word) u) + ((mp_word) * tmpx);
076
077             /* get carry */
078             u          = (mp_digit)(r >> ((mp_word) DIGIT_BIT));
079
080             /* fix digit */

```



```

081         *tmpx++ = (mp_digit)(r & ((mp_word) MP_MASK));
082     }
083     /* At this point the ix'th digit of x should be zero */
084
085
086     /* propagate carries upwards as required*/
087     while (u) {
088         *tmpx += u;
089         u = *tmpx >> DIGIT_BIT;
090         *tmpx++ &= MP_MASK;
091     }
092 }
093 }
094
095 /* at this point the n.used'th least
096 * significant digits of x are all zero
097 * which means we can shift x to the
098 * right by n.used digits and the
099 * residue is unchanged.
100 */
101
102 /* x = x/b**n.used */
103 mp_clamp(x);
104 mp_rshd (x, n->used);
105
106 /* if x >= n then x = x - n */
107 if (mp_cmp_mag (x, n) != MP_LT) {
108     return s_mp_sub (x, n, x);
109 }
110
111 return MP_OKAY;
112 }

```

This is the baseline implementation of the Montgomery reduction algorithm. Lines 30 to 35 determine if the Comba based routine can be used instead. Line 48 computes the value of μ for that particular iteration of the outer loop.

The multiplication $\mu n \beta^{ix}$ is performed in one step in the inner loop. The alias *tmpx* refers to the *ix*'th digit of *x* and the alias *tmpn* refers to the modulus *n*.

6.3.3 Faster “Comba” Montgomery Reduction

The Montgomery reduction requires fewer single precision multiplications than a Barrett reduction, however it is much slower due to the serial nature of the inner loop. The Barrett reduction algorithm requires two slightly modified multipliers which can be implemented with the Comba technique. The Montgomery reduction algorithm cannot directly use the Comba technique to any significant advantage since the inner loop calculates a $k \times 1$ product k times.

The biggest obstacle is that at the ix 'th iteration of the outer loop the value of x_{ix} is required to calculate μ . This means the carries from 0 to $ix - 1$ must have been propagated upwards to form a valid ix 'th digit. The solution as it turns out is very simple. Perform a Comba like multiplier and inside the outer loop just after the inner loop fix up the $ix + 1$ 'th digit by forwarding the carry.

With this change in place the Montgomery reduction algorithm can be performed with a Comba style multiplication loop which substantially increases the speed of the algorithm.

Algorithm **fast_mp_montgomery_reduce**.

Input. mp_int x , mp_int n and a digit $\rho \equiv -1/n_0 \pmod{n}$.
 $(0 \leq x < n^2, n > 1, (n, \beta) = 1, \beta^k > n)$

Output. $\beta^{-k}x \pmod{n}$

Place an array of **MP_WARRAY** mp_word variables called \hat{W} on the stack.

1. if $x.alloc < n.used + 1$ then grow x to $n.used + 1$ digits.

Copy the digits of x into the array \hat{W}

2. For ix from 0 to $x.used - 1$ do

2.1 $\hat{W}_{ix} \leftarrow x_{ix}$

3. For ix from $x.used$ to $2n.used - 1$ do

3.1 $\hat{W}_{ix} \leftarrow 0$

Eliminate the lower k digits.

4. for ix from 0 to $n.used - 1$ do

4.1 $\mu \leftarrow \hat{W}_{ix} \cdot \rho \pmod{\beta}$

4.2 For iy from 0 to $n.used - 1$ do

4.2.1 $\hat{W}_{iy+ix} \leftarrow \hat{W}_{iy+ix} + \mu \cdot n_{iy}$

4.3 $\hat{W}_{ix+1} \leftarrow \hat{W}_{ix+1} + \lfloor \hat{W}_{ix}/\beta \rfloor$

Propagate carries upwards.

5. for ix from $n.used$ to $2n.used + 1$ do

5.1 $\hat{W}_{ix+1} \leftarrow \hat{W}_{ix+1} + \lfloor \hat{W}_{ix}/\beta \rfloor$

Shift right and reduce modulo β simultaneously.

6. for ix from 0 to $n.used + 1$ do

6.1 $x_{ix} \leftarrow \hat{W}_{ix+n.used} \pmod{\beta}$

Zero excess digits and fixup x .

7. if $x.used > n.used + 1$ then do

7.1 for ix from $n.used + 1$ to $x.used - 1$ do

7.1.1 $x_{ix} \leftarrow 0$

8. $x.used \leftarrow n.used + 1$

9. Clamp excessive digits of x .

10. If $x \geq n$ then

10.1 $x \leftarrow x - n$

11. Return(*MP_OKAY*).

Figure 6.10: Algorithm fast_mp_montgomery_reduce

Algorithm fast_mp_montgomery_reduce. This algorithm will compute the Montgomery reduction of x modulo n using the Comba technique. It is on most computer platforms significantly faster than algorithm mp_montgomery_reduce and algorithm mp_reduce (*Barrett reduction*). The algorithm has the same re-

restrictions on the input as the baseline reduction algorithm. An additional two restrictions are imposed on this algorithm. The number of digits k in the the modulus n must not violate $MP_WARRAY > 2k+1$ and $n < \delta$. When $\beta = 2^{28}$ this algorithm can be used to reduce modulo a modulus of at most 3,556 bits in length.

As in the other Comba reduction algorithms there is a \hat{W} array which stores the columns of the product. It is initially filled with the contents of x with the excess digits zeroed. The reduction loop is very similar the to the baseline loop at heart. The multiplication on step 4.1 can be single precision only since $ab \pmod{\beta} \equiv (a \pmod{\beta})(b \pmod{\beta})$. Some multipliers such as those on the ARM processors take a variable length time to complete depending on the number of bytes of result it must produce. By performing a single precision multiplication instead half the amount of time is spent.

Also note that digit \hat{W}_{ix} must have the carry from the $ix - 1$ 'th digit propagated upwards in order for this to work. That is what step 4.3 will do. In effect over the $n.used$ iterations of the outer loop the $n.used$ 'th lower columns all have the their carries propagated forwards. Note how the upper bits of those same words are not reduced modulo β . This is because those values will be discarded shortly and there is no point.

Step 5 will propagate the remainder of the carries upwards. On step 6 the columns are reduced modulo β and shifted simultaneously as they are stored in the destination x .

File: bn_fast_mp_montgomery_reduce.c

```

016
017  /* computes xR**(-1) == x (mod N) via Montgomery Reduction
018  *
019  * This is an optimized implementation of mp_montgomery_reduce
020  * which uses the comba method to quickly calculate the columns of the
021  * reduction.
022  *
023  * Based on Algorithm 14.32 on pp.601 of HAC.
024  */
025  int
026  fast_mp_montgomery_reduce (mp_int * x, mp_int * n, mp_digit rho)
027  {
028      int      ix, res, olduse;
029      mp_word W[MP_WARRAY];
030
031      /* get old used count */
032      olduse = x->used;

```

```

033
034  /* grow a as required */
035  if (x->alloc < n->used + 1) {
036      if ((res = mp_grow (x, n->used + 1)) != MP_OKAY) {
037          return res;
038      }
039  }
040
041  /* first we have to get the digits of the input into
042   * an array of double precision words W[...]
043   */
044  {
045      register mp_word *_W;
046      register mp_digit *tmpx;
047
048      /* alias for the W[] array */
049      _W = W;
050
051      /* alias for the digits of x*/
052      tmpx = x->dp;
053
054      /* copy the digits of a into W[0..a->used-1] */
055      for (ix = 0; ix < x->used; ix++) {
056          *_W++ = *tmpx++;
057      }
058
059      /* zero the high words of W[a->used..m->used*2] */
060      for (; ix < n->used * 2 + 1; ix++) {
061          *_W++ = 0;
062      }
063  }
064
065  /* now we proceed to zero successive digits
066   * from the least significant upwards
067   */
068  for (ix = 0; ix < n->used; ix++) {
069      /* mu = ai * m' mod b
070       *
071       * We avoid a double precision multiplication (which isn't required)
072       * by casting the value down to a mp_digit. Note this requires
073       * that W[ix-1] have the carry cleared (see after the inner loop)
074       */

```

```

075     register mp_digit mu;
076     mu = (mp_digit) (((W[ix] & MP_MASK) * rho) & MP_MASK);
077
078     /* a = a + mu * m * b**i
079     *
080     * This is computed in place and on the fly. The multiplication
081     * by b**i is handled by offseting which columns the results
082     * are added to.
083     *
084     * Note the comba method normally doesn't handle carries in the
085     * inner loop In this case we fix the carry from the previous
086     * column since the Montgomery reduction requires digits of the
087     * result (so far) [see above] to work. This is
088     * handled by fixing up one carry after the inner loop. The
089     * carry fixups are done in order so after these loops the
090     * first m->used words of W[] have the carries fixed
091     */
092     {
093         register int iy;
094         register mp_digit *tmpn;
095         register mp_word *_W;
096
097         /* alias for the digits of the modulus */
098         tmpn = n->dp;
099
100         /* Alias for the columns set by an offset of ix */
101         _W = W + ix;
102
103         /* inner loop */
104         for (iy = 0; iy < n->used; iy++) {
105             *_W++ += ((mp_word)mu) * ((mp_word)*tmpn++);
106         }
107     }
108
109     /* now fix carry for next digit, W[ix+1] */
110     W[ix + 1] += W[ix] >> ((mp_word) DIGIT_BIT);
111 }
112
113 /* now we have to propagate the carries and
114 * shift the words downward [all those least
115 * significant digits we zeroed].
116 */

```

```

117     {
118         register mp_digit *tmpx;
119         register mp_word *_W, *_W1;
120
121         /* nox fix rest of carries */
122
123         /* alias for current word */
124         _W1 = W + ix;
125
126         /* alias for next word, where the carry goes */
127         _W = W + ++ix;
128
129         for (; ix <= n->used * 2 + 1; ix++) {
130             *_W++ += *_W1++ >> ((mp_word) DIGIT_BIT);
131         }
132
133         /* copy out, A = A/b**n
134          *
135          * The result is A/b**n but instead of converting from an
136          * array of mp_word to mp_digit than calling mp_rshd
137          * we just copy them in the right order
138          */
139
140         /* alias for destination word */
141         tmpx = x->dp;
142
143         /* alias for shifted double precision result */
144         _W = W + n->used;
145
146         for (ix = 0; ix < n->used + 1; ix++) {
147             *tmpx++ = (mp_digit)(* _W++ & ((mp_word) MP_MASK));
148         }
149
150         /* zero oldused digits, if the input a was larger than
151          * m->used+1 we'll have to clear the digits
152          */
153         for (; ix < olduse; ix++) {
154             *tmpx++ = 0;
155         }
156     }
157
158     /* set the max used and clamp */

```

```

159     x->used = n->used + 1;
160     mp_clamp (x);
161
162     /* if A >= m then A = A - m */
163     if (mp_cmp_mag (x, n) != MP_LT) {
164         return s_mp_sub (x, n, x);
165     }
166     return MP_OKAY;
167 }

```

The \hat{W} array is first filled with digits of x on line 48 then the rest of the digits are zeroed on line 55. Both loops share the same alias variables to make the code easier to read.

The value of μ is calculated in an interesting fashion. First the value \hat{W}_{ix} is reduced modulo β and cast to a mp_digit. This forces the compiler to use a single precision multiplication and prevents any concerns about loss of precision. Line 110 fixes the carry for the next iteration of the loop by propagating the carry from \hat{W}_{ix} to \hat{W}_{ix+1} .

The for loop on line 109 propagates the rest of the carries upwards through the columns. The for loop on line 126 reduces the columns modulo β and shifts them k places at the same time. The alias \hat{W} actually refers to the array \hat{W} starting at the $n.used$ 'th digit, that is $\hat{W}_t = \hat{W}_{n.used+t}$.

6.3.4 Montgomery Setup

To calculate the variable ρ a relatively simple algorithm will be required.

Algorithm **mp_montgomery_setup**.
Input. mp_int n ($n > 1$ and $(n, 2) = 1$)
Output. $\rho \equiv -1/n_0 \pmod{\beta}$

1. $b \leftarrow n_0$
2. If b is even return(MP_VAL)
3. $x \leftarrow ((b + 2) \text{ AND } 4) \lll 1 + b$
4. for k from 0 to $\lceil \lg(\lg(\beta)) \rceil - 2$ do
 - 4.1 $x \leftarrow x \cdot (2 - bx)$
5. $\rho \leftarrow \beta - x \pmod{\beta}$
6. Return(MP_OKAY).

Figure 6.11: Algorithm mp_montgomery_setup

Algorithm mp_montgomery_setup. This algorithm will calculate the value of ρ required within the Montgomery reduction algorithms. It uses a very interesting trick to calculate $1/n_0$ when β is a power of two.

File: bn_mp_montgomery_setup.c

```

016
017  /* setups the montgomery reduction stuff */
018  int
019  mp_montgomery_setup (mp_int * n, mp_digit * rho)
020  {
021      mp_digit x, b;
022
023      /* fast inversion mod 2**k
024       *
025       * Based on the fact that
026       *
027       *  $XA = 1 \pmod{2^{**n}} \Rightarrow (X(2-XA))A = 1 \pmod{2^{**2n}}$ 
028       *  $\Rightarrow 2XA - XXA^2 = 1$ 
029       *  $\Rightarrow 2(1) - (1) = 1$ 
030       */
031      b = n->dp[0];
032
033      if ((b & 1) == 0) {
034          return MP_VAL;
035      }
036
037      x = (((b + 2) & 4) << 1) + b; /* here x*a==1 mod 2**4 */
038      x *= 2 - b * x;             /* here x*a==1 mod 2**8 */
039      #if !defined(MP_8BIT)
040      x *= 2 - b * x;             /* here x*a==1 mod 2**16 */
041      #endif
042      #if defined(MP_64BIT) || !(defined(MP_8BIT) || defined(MP_16BIT))
043      x *= 2 - b * x;             /* here x*a==1 mod 2**32 */
044      #endif
045      #ifdef MP_64BIT
046      x *= 2 - b * x;             /* here x*a==1 mod 2**64 */
047      #endif
048
049      /* rho = -1/m mod b */
050      *rho = (((mp_digit) 1 << ((mp_digit) DIGIT_BIT)) - x) & MP_MASK;
051
052      return MP_OKAY;

```

053 }

This source code computes the value of ρ required to perform Montgomery reduction. It has been modified to avoid performing excess multiplications when β is not the default 28-bits.

6.4 The Diminished Radix Algorithm

The Diminished Radix method of modular reduction [9] is a fairly clever technique which can be more efficient than either the Barrett or Montgomery methods for certain forms of moduli. The technique is based on the following simple congruence.

$$(x \bmod n) + k \lfloor x/n \rfloor \equiv x \pmod{(n - k)} \quad (6.6)$$

This observation was used in the MMB [10] block cipher to create a diffusion primitive. It used the fact that if $n = 2^{31}$ and $k = 1$ that then a x86 multiplier could produce the 62-bit product and use the “shrd” instruction to perform a double-precision right shift. The proof of the above equation is very simple. First write x in the product form.

$$x = qn + r \quad (6.7)$$

Now reduce both sides modulo $(n - k)$.

$$x \equiv qk + r \pmod{(n - k)} \quad (6.8)$$

The variable n reduces modulo $n - k$ to k . By putting $q = \lfloor x/n \rfloor$ and $r = x \bmod n$ into the equation the original congruence is reproduced, thus concluding the proof. The following algorithm is based on this observation.

This algorithm will reduce x modulo $n - k$ and return the residue. If $0 \leq x < (n - k)^2$ then the algorithm will loop almost always once or twice and occasionally three times. For simplicity sake the value of x is bounded by the following simple polynomial.

$$0 \leq x < n^2 + k^2 - 2nk \quad (6.9)$$

The true bound is $0 \leq x < (n - k - 1)^2$ but this has quite a few more terms. The value of q after step 1 is bounded by the following.

$$q < n - 2k - k^2/n \quad (6.10)$$

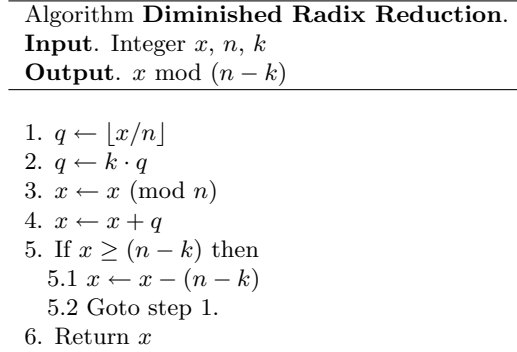


Figure 6.12: Algorithm Diminished Radix Reduction

Since k^2 is going to be considerably smaller than n that term will always be zero. The value of x after step 3 is bounded trivially as $0 \leq x < n$. By step four the sum $x + q$ is bounded by

$$0 \leq q + x < (k + 1)n - 2k^2 - 1 \quad (6.11)$$

With a second pass q will be loosely bounded by $0 \leq q < k^2$ after step 2 while x will still be loosely bounded by $0 \leq x < n$ after step 3. After the second pass it is highly unlikely that the sum in step 4 will exceed $n - k$. In practice fewer than three passes of the algorithm are required to reduce virtually every input in the range $0 \leq x < (n - k - 1)^2$.

Figure 6.13 demonstrates the reduction of $x = 123456789$ modulo $n - k = 253$ when $n = 256$ and $k = 3$. Note that even while x is considerably larger than $(n - k - 1)^2 = 63504$ the algorithm still converges on the modular residue exceedingly fast. In this case only three passes were required to find the residue $x \equiv 126$.

6.4.1 Choice of Moduli

On the surface this algorithm looks like a very expensive algorithm. It requires a couple of subtractions followed by multiplication and other modular reductions. The usefulness of this algorithm becomes exceedingly clear when an appropriate modulus is chosen.

$x = 123456789, n = 256, k = 3$
$q \leftarrow \lfloor x/n \rfloor = 482253$
$q \leftarrow q * k = 1446759$
$x \leftarrow x \bmod n = 21$
$x \leftarrow x + q = 1446780$
$x \leftarrow x - (n - k) = 1446527$
$q \leftarrow \lfloor x/n \rfloor = 5650$
$q \leftarrow q * k = 16950$
$x \leftarrow x \bmod n = 127$
$x \leftarrow x + q = 17077$
$x \leftarrow x - (n - k) = 16824$
$q \leftarrow \lfloor x/n \rfloor = 65$
$q \leftarrow q * k = 195$
$x \leftarrow x \bmod n = 184$
$x \leftarrow x + q = 379$
$x \leftarrow x - (n - k) = 126$

Figure 6.13: Example Diminished Radix Reduction

Division in general is a very expensive operation to perform. The one exception is when the division is by a power of the radix of representation used. Division by ten for example is simple for pencil and paper mathematics since it amounts to shifting the decimal place to the right. Similarly division by two (*or powers of two*) is very simple for binary computers to perform. It would therefore seem logical to choose n of the form 2^p which would imply that $\lfloor x/n \rfloor$ is a simple shift of x right p bits.

However, there is one operation related to division of power of twos that is even faster than this. If $n = \beta^p$ then the division may be performed by moving whole digits to the right p places. In practice division by β^p is much faster than division by 2^p for any p . Also with the choice of $n = \beta^p$ reducing x modulo n merely requires zeroing the digits above the $p - 1$ 'th digit of x .

Throughout the next section the term “restricted modulus” will refer to a modulus of the form $\beta^p - k$ whereas the term “unrestricted modulus” will refer to a modulus of the form $2^p - k$. The word “restricted” in this case refers to the fact that it is based on the 2^p logic except p must be a multiple of $\lg(\beta)$.

6.4.2 Choice of k

Now that division and reduction (*step 1 and 3 of figure 6.12*) have been optimized to simple digit operations the multiplication by k in step 2 is the most expensive operation. Fortunately the choice of k is not terribly limited. For all intents and purposes it might as well be a single digit. The smaller the value of k is the faster the algorithm will be.

6.4.3 Restricted Diminished Radix Reduction

The restricted Diminished Radix algorithm can quickly reduce an input modulo a modulus of the form $n = \beta^p - k$. This algorithm can reduce an input x within the range $0 \leq x < n^2$ using only a couple passes of the algorithm demonstrated in figure 6.12. The implementation of this algorithm has been optimized to avoid additional overhead associated with a division by β^p , the multiplication by k or the addition of x and q . The resulting algorithm is very efficient and can lead to substantial improvements over Barrett and Montgomery reduction when modular exponentiations are performed.

Algorithm **mp_dr_reduce**.

Input. mp_int x , n and a mp_digit $k = \beta - n_0$
 $(0 \leq x < n^2, n > 1, 0 < k < \beta)$

Output. $x \bmod n$

1. $m \leftarrow n.used$
 2. If $x.alloc < 2m$ then grow x to $2m$ digits.
 3. $\mu \leftarrow 0$
 4. for i from 0 to $m - 1$ do
 - 4.1 $\hat{r} \leftarrow k \cdot x_{m+i} + x_i + \mu$
 - 4.2 $x_i \leftarrow \hat{r} \pmod{\beta}$
 - 4.3 $\mu \leftarrow \lfloor \hat{r} / \beta \rfloor$
 5. $x_m \leftarrow \mu$
 6. for i from $m + 1$ to $x.used - 1$ do
 - 6.1 $x_i \leftarrow 0$
 7. Clamp excess digits of x .
 8. If $x \geq n$ then
 - 8.1 $x \leftarrow x - n$
 - 8.2 Goto step 3.
 9. Return(*MP_OKAY*).
-

Figure 6.14: Algorithm mp_dr_reduce

Algorithm mp_dr_reduce. This algorithm will perform the Diminished Radix reduction of x modulo n . It has similar restrictions to that of the Barrett reduction with the addition that n must be of the form $n = \beta^m - k$ where $0 < k < \beta$.

This algorithm essentially implements the pseudo-code in figure 6.12 except with a slight optimization. The division by β^m , multiplication by k and addition of $x \bmod \beta^m$ are all performed simultaneously inside the loop on step 4. The division by β^m is emulated by accessing the term at the $m + i$ 'th position which is subsequently multiplied by k and added to the term at the i 'th position. After the loop the m 'th digit is set to the carry and the upper digits are zeroed. Steps 5 and 6 emulate the reduction modulo β^m that should have happened to x before the addition of the multiple of the upper half.

At step 8 if x is still larger than n another pass of the algorithm is required. First n is subtracted from x and then the algorithm resumes at step 3.

File: bn_mp_dr_reduce.c

016

017 /* reduce "x" in place modulo "n" using the Diminished Radix algorithm.

```

018  *
019  * Based on algorithm from the paper
020  *
021  * "Generating Efficient Primes for Discrete Log Cryptosystems"
022  *           Chae Hoon Lim, Pil Loong Lee,
023  *           POSTECH Information Research Laboratories
024  *
025  * The modulus must be of a special format [see manual]
026  *
027  * Has been modified to use algorithm 7.10 from the LTM book instead
028  *
029  * Input x must be in the range  $0 \leq x \leq (n-1)**2$ 
030  */
031  int
032  mp_dr_reduce (mp_int * x, mp_int * n, mp_digit k)
033  {
034      int      err, i, m;
035      mp_word  r;
036      mp_digit mu, *tmpx1, *tmpx2;
037
038      /* m = digits in modulus */
039      m = n->used;
040
041      /* ensure that "x" has at least 2m digits */
042      if (x->alloc < m + m) {
043          if ((err = mp_grow (x, m + m)) != MP_OKAY) {
044              return err;
045          }
046      }
047
048      /* top of loop, this is where the code resumes if
049      * another reduction pass is required.
050      */
051      top:
052      /* aliases for digits */
053      /* alias for lower half of x */
054      tmpx1 = x->dp;
055
056      /* alias for upper half of x, or  $x/B^{**m}$  */
057      tmpx2 = x->dp + m;
058
059      /* set carry to zero */

```

```

060     mu = 0;
061
062     /* compute (x mod B**m) + k * [x/B**m] inline and inplace */
063     for (i = 0; i < m; i++) {
064         r          = ((mp_word)*tmpx2++) * ((mp_word)k) + *tmpx1 + mu;
065         *tmpx1++   = (mp_digit)(r & MP_MASK);
066         mu        = (mp_digit)(r >> ((mp_word)DIGIT_BIT));
067     }
068
069     /* set final carry */
070     *tmpx1++ = mu;
071
072     /* zero words above m */
073     for (i = m + 1; i < x->used; i++) {
074         *tmpx1++ = 0;
075     }
076
077     /* clamp, sub and return */
078     mp_clamp (x);
079
080     /* if x >= n then subtract and reduce again
081      * Each successive "recursion" makes the input smaller and smaller.
082      */
083     if (mp_cmp_mag (x, n) != MP_LT) {
084         s_mp_sub(x, n, x);
085         goto top;
086     }
087     return MP_OKAY;
088 }

```

The first step is to grow x as required to $2m$ digits since the reduction is performed in place on x . The label on line 51 is where the algorithm will resume if further reduction passes are required. In theory it could be placed at the top of the function however, the size of the modulus and question of whether x is large enough are invariant after the first pass meaning that it would be a waste of time.

The aliases $tmpx1$ and $tmpx2$ refer to the digits of x where the latter is offset by m digits. By reading digits from x offset by m digits a division by β^m can be simulated virtually for free. The loop on line 63 performs the bulk of the work (*corresponds to step 4 of algorithm 7.11*) in this algorithm.

By line 70 the pointer $tmpx1$ points to the m 'th digit of x which is where the final carry will be placed. Similarly by line 73 the same pointer will point

to the $m + 1$ 'th digit where the zeroes will be placed.

Since the algorithm is only valid if both x and n are greater than zero an unsigned comparison suffices to determine if another pass is required. With the same logic at line 84 the value of x is known to be greater than or equal to n meaning that an unsigned subtraction can be used as well. Since the destination of the subtraction is the larger of the inputs the call to algorithm `s_mp_sub` cannot fail and the return code does not need to be checked.

Setup

To setup the restricted Diminished Radix algorithm the value $k = \beta - n_0$ is required. This algorithm is not really complicated but provided for completeness.

Algorithm **mp_dr_setup**.
Input. mp_int n
Output. $k = \beta - n_0$

1. $k \leftarrow \beta - n_0$

Figure 6.15: Algorithm `mp_dr_setup`

```

File: bn_mp_dr_setup.c
016
017  /* determines the setup value */
018  void mp_dr_setup(mp_int *a, mp_digit *d)
019  {
020      /* the casts are required if DIGIT_BIT is one less than
021       * the number of bits in a mp_digit [e.g. DIGIT_BIT==31]
022       */
023      *d = (mp_digit)((((mp_word)1) << ((mp_word)DIGIT_BIT)) -
024                ((mp_word)a->dp[0]));
025  }
026

```

Modulus Detection

Another algorithm which will be useful is the ability to detect a restricted Diminished Radix modulus. An integer is said to be of restricted Diminished Radix form if all of the digits are equal to $\beta - 1$ except the trailing digit which may be any value.

Algorithm **mp_dr_is_modulus**.
Input. mp_int n
Output. 1 if n is in D.R form, 0 otherwise

1. If $n.used < 2$ then return(0).
2. for ix from 1 to $n.used - 1$ do
 - 2.1 If $n_{ix} \neq \beta - 1$ return(0).
3. Return(1).

Figure 6.16: Algorithm mp_dr_is_modulus

Algorithm mp_dr_is_modulus. This algorithm determines if a value is in Diminished Radix form. Step 1 rejects obvious cases where fewer than two digits are in the mp_int. Step 2 tests all but the first digit to see if they are equal to $\beta - 1$. If the algorithm manages to get to step 3 then n must be of Diminished Radix form.

File: bn_mp_dr_is_modulus.c

```

016
017 /* determines if a number is a valid DR modulus */
018 int mp_dr_is_modulus(mp_int *a)
019 {
020     int ix;
021
022     /* must be at least two digits */
023     if (a->used < 2) {
024         return 0;
025     }
026
027     /* must be of the form b**k - a [a <= b] so all
028      * but the first digit must be equal to -1 (mod b).
029     */
030     for (ix = 1; ix < a->used; ix++) {
031         if (a->dp[ix] != MP_MASK) {
032             return 0;
033         }
034     }
035     return 1;
036 }
037

```

6.4.4 Unrestricted Diminished Radix Reduction

The unrestricted Diminished Radix algorithm allows modular reductions to be performed when the modulus is of the form $2^p - k$. This algorithm is a straightforward adaptation of algorithm 6.12.

In general the restricted Diminished Radix reduction algorithm is much faster since it has considerably lower overhead. However, this new algorithm is much faster than either Montgomery or Barrett reduction when the moduli are of the appropriate form.

Algorithm **mp_reduce_2k**.
Input. mp_int a and n . mp_digit k
 $(a \geq 0, n > 1, 0 < k < \beta, n + k$ is a power of two)
Output. $a \pmod{n}$

1. $p \leftarrow \lceil \lg(n) \rceil$ (*mp_count_bits*)
2. While $a \geq n$ do
 - 2.1 $q \leftarrow \lfloor a/2^p \rfloor$ (*mp_div_2d*)
 - 2.2 $a \leftarrow a \pmod{2^p}$ (*mp_mod_2d*)
 - 2.3 $q \leftarrow q \cdot k$ (*mp_mul_d*)
 - 2.4 $a \leftarrow a - q$ (*s_mp_sub*)
 - 2.5 If $a \geq n$ then do
 - 2.5.1 $a \leftarrow a - n$
3. Return(*MP_OKAY*).

Figure 6.17: Algorithm mp_reduce_2k

Algorithm mp_reduce_2k. This algorithm quickly reduces an input a modulo an unrestricted Diminished Radix modulus n . Division by 2^p is emulated with a right shift which makes the algorithm fairly inexpensive to use.

File: bn_mp_reduce_2k.c

```

016
017  /* reduces a modulo n where n is of the form 2**p - k */
018  int
019  mp_reduce_2k(mp_int *a, mp_int *n, mp_digit k)
020  {
021      mp_int q;
022      int    p, res;
023
024      if ((res = mp_init(&q)) != MP_OKAY) {
025          return res;

```

```

026     }
027
028     p = mp_count_bits(n);
029 top:
030     /* q = a/2**p, a = a mod 2**p */
031     if ((res = mp_div_2d(a, p, &q, a)) != MP_OKAY) {
032         goto ERR;
033     }
034
035     if (k != 1) {
036         /* q = q * k */
037         if ((res = mp_mul_d(&q, k, &q)) != MP_OKAY) {
038             goto ERR;
039         }
040     }
041
042     /* a = a + q */
043     if ((res = s_mp_add(a, &q, a)) != MP_OKAY) {
044         goto ERR;
045     }
046
047     if (mp_cmp_mag(a, n) != MP_LT) {
048         s_mp_sub(a, n, a);
049         goto top;
050     }
051
052 ERR:
053     mp_clear(&q);
054     return res;
055 }
056

```

The algorithm `mp_count_bits` calculates the number of bits in an `mp_int` which is used to find the initial value of p . The call to `mp_div_2d` on line 31 calculates both the quotient q and the remainder a required. By doing both in a single function call the code size is kept fairly small. The multiplication by k is only performed if $k > 1$. This allows reductions modulo $2^p - 1$ to be performed without any multiplications.

The unsigned `s_mp_add`, `mp_cmp_mag` and `s_mp_sub` are used in place of their full sign counterparts since the inputs are only valid if they are positive. By using the unsigned versions the overhead is kept to a minimum.

Unrestricted Setup

To setup this reduction algorithm the value of $k = 2^p - n$ is required.

Algorithm mp_reduce_2k_setup .
Input. mp_int n
Output. $k = 2^p - n$
1. $p \leftarrow \lceil \lg(n) \rceil$ (<i>mp_count_bits</i>)
2. $x \leftarrow 2^p$ (<i>mp_2expt</i>)
3. $x \leftarrow x - n$ (<i>mp_sub</i>)
4. $k \leftarrow x_0$
5. Return(<i>MP_OKAY</i>).

Figure 6.18: Algorithm mp_reduce_2k_setup

Algorithm mp_reduce_2k_setup. This algorithm computes the value of k required for the algorithm mp_reduce_2k. By making a temporary variable x equal to 2^p a subtraction is sufficient to solve for k . Alternatively if n has more than one digit the value of k is simply $\beta - n_0$.

File: bn_mp_reduce_2k_setup.c

```

016
017  /* determines the setup value */
018  int
019  mp_reduce_2k_setup(mp_int *a, mp_digit *d)
020  {
021      int res, p;
022      mp_int tmp;
023
024      if ((res = mp_init(&tmp)) != MP_OKAY) {
025          return res;
026      }
027
028      p = mp_count_bits(a);
029      if ((res = mp_2expt(&tmp, p)) != MP_OKAY) {
030          mp_clear(&tmp);
031          return res;
032      }
033
034      if ((res = s_mp_sub(&tmp, a, &tmp)) != MP_OKAY) {
035          mp_clear(&tmp);
036          return res;

```

```

037     }
038
039     *d = tmp.dp[0];
040     mp_clear(&tmp);
041     return MP_OKAY;
042 }

```

Unrestricted Detection

An integer n is a valid unrestricted Diminished Radix modulus if either of the following are true.

1. The number has only one digit.
2. The number has more than one digit and every bit from the β 'th to the most significant is one.

If either condition is true then there is a power of two 2^p such that $0 < 2^p - n < \beta$. If the input is only one digit then it will always be of the correct form. Otherwise all of the bits above the first digit must be one. This arises from the fact that there will be value of k that when added to the modulus causes a carry in the first digit which propagates all the way to the most significant bit. The resulting sum will be a power of two.

Algorithm mp_reduce_is_2k.

Input. mp_int n

Output. 1 if of proper form, 0 otherwise

1. If $n.used = 0$ then return(0).
 2. If $n.used = 1$ then return(1).
 3. $p \leftarrow \lceil \lg(n) \rceil$ (mp_count_bits)
 4. for x from $\lg(\beta)$ to p do
 - 4.1 If the $(x \bmod \lg(\beta))$ 'th bit of the $\lfloor x/\lg(\beta) \rfloor$ of n is zero then return(0).
 5. Return(1).
-

Figure 6.19: Algorithm mp_reduce_is_2k

Algorithm mp_reduce_is_2k. This algorithm quickly determines if a modulus is of the form required for algorithm mp_reduce_2k to function properly.

File: bn_mp_reduce_is_2k.c

```

016
017  /* determines if mp_reduce_2k can be used */
018  int mp_reduce_is_2k(mp_int *a)
019  {
020      int ix, iy, iz, iw;
021
022      if (a->used == 0) {
023          return 0;
024      } else if (a->used == 1) {
025          return 1;
026      } else if (a->used > 1) {
027          iy = mp_count_bits(a);
028          iz = 1;
029          iw = 1;
030
031          /* Test every bit from the second digit up, must be 1 */
032          for (ix = DIGIT_BIT; ix < iy; ix++) {
033              if ((a->dp[ix] & iz) == 0) {
034                  return 0;
035              }
036              iz <<= 1;
037              if (iz > (int)MP_MASK) {
038                  ++iw;
039                  iz = 1;
040              }
041          }
042      }
043      return 1;
044  }
045

```

6.5 Algorithm Comparison

So far three very different algorithms for modular reduction have been discussed. Each of the algorithms have their own strengths and weaknesses that makes having such a selection very useful. The following table summarizes the three algorithms along with comparisons of work factors. Since all three algorithms have the restriction that $0 \leq x < n^2$ and $n > 1$ those limitations are not included in the table.

Method	Work Required	Limitations	$m = 8$	$m = 32$	$m = 64$
Barrett	$m^2 + 2m - 1$	None	79	1087	4223
Montgomery	$m^2 + m$	n must be odd	72	1056	4160
D.R.	$2m$	$n = \beta^m - k$	16	64	128

In theory Montgomery and Barrett reductions would require roughly the same amount of time to complete. However, in practice since Montgomery reduction can be written as a single function with the Comba technique it is much faster. Barrett reduction suffers from the overhead of calling the half precision multipliers, addition and division by β algorithms.

For almost every cryptographic algorithm Montgomery reduction is the algorithm of choice. The one set of algorithms where Diminished Radix reduction truly shines are based on the discrete logarithm problem such as Diffie-Hellman [?] and ElGamal [?]. In these algorithms primes of the form $\beta^m - k$ can be found and shared amongst users. These primes will allow the Diminished Radix algorithm to be used in modular exponentiation to greatly speed up the operation.

Exercises

- [3] Prove that the “trick” in algorithm `mp_montgomery_setup` actually calculates the correct value of ρ .
- [2] Devise an algorithm to reduce modulo $n + k$ for small k quickly.
- [4] Prove that the pseudo-code algorithm “Diminished Radix Reduction” (*figure 6.12*) terminates. Also prove the probability that it will terminate within $1 \leq k \leq 10$ iterations.

Chapter 7

Exponentiation

Exponentiation is the operation of raising one variable to the power of another, for example, a^b . A variant of exponentiation, computed in a finite field or ring, is called modular exponentiation. This latter style of operation is typically used in public key cryptosystems such as RSA and Diffie-Hellman. The ability to quickly compute modular exponentiations is of great benefit to any such cryptosystem and many methods have been sought to speed it up.

7.1 Exponentiation Basics

A trivial algorithm would simply multiply a against itself $b - 1$ times to compute the exponentiation desired. However, as b grows in size the number of multiplications becomes prohibitive. Imagine what would happen if $b \sim 2^{1024}$ as is the case when computing an RSA signature with a 1024-bit key. Such a calculation could never be completed as it would take simply far too long.

Fortunately there is a very simple algorithm based on the laws of exponents. Recall that $\lg_a(a^b) = b$ and that $\lg_a(a^b a^c) = b + c$ which are two trivial relationships between the base and the exponent. Let b_i represent the i 'th bit of b starting from the least significant bit. If b is a k -bit integer then the following equation is true.

$$a^b = \prod_{i=0}^{k-1} a^{2^i \cdot b_i} \quad (7.1)$$

By taking the base a logarithm of both sides of the equation the following equation is the result.

$$b = \sum_{i=0}^{k-1} 2^i \cdot b_i \quad (7.2)$$

The term a^{2^i} can be found from the $i - 1$ 'th term by squaring the term since $(a^{2^{i-1}})^2$ is equal to a^{2^i} . This observation forms the basis of essentially all fast exponentiation algorithms. It requires k squarings and on average $\frac{k}{2}$ multiplications to compute the result. This is indeed quite an improvement over simply multiplying by a a total of $b - 1$ times.

While this current method is a considerable speed up there are further improvements to be made. For example, the a^{2^i} term does not need to be computed in an auxiliary variable. Consider the following equivalent algorithm.

Algorithm Left to Right Exponentiation.

Input. Integer a , b and k

Output. $c = a^b$

1. $c \leftarrow 1$
 2. for i from $k - 1$ to 0 do
 - 2.1 $c \leftarrow c^2$
 - 2.2 $c \leftarrow c \cdot a^{b_i}$
 3. Return c .
-

Figure 7.1: Left to Right Exponentiation

This algorithm starts from the most significant bit and works towards the least significant bit. When the i 'th bit of b is set a is multiplied against the current product. In each iteration the product is squared which doubles the exponent of the individual terms of the product.

For example, let $b = 101100_2 \equiv 44_{10}$. The following chart demonstrates the actions of the algorithm.

Value of i	Value of c
-	1
5	a
4	a^2
3	$a^4 \cdot a$
2	$a^8 \cdot a^2 \cdot a$
1	$a^{16} \cdot a^4 \cdot a^2$
0	$a^{32} \cdot a^8 \cdot a^4$

Figure 7.2: Example of Left to Right Exponentiation

When the product $a^{32} \cdot a^8 \cdot a^4$ is simplified it is equal a^{44} which is the desired exponentiation. This particular algorithm is called “Left to Right” because it reads the exponent in that order. All of the exponentiation algorithms that will be presented are of this nature.

7.1.1 Single Digit Exponentiation

The first algorithm in the series of exponentiation algorithms will be an unbounded algorithm where the exponent is a single digit. It is intended to be used when a small power of an input is required (*e.g.* a^5). It is faster than simply multiplying $b - 1$ times for all values of b that are greater than three.

Algorithm **mp_expt_d**.
Input. mp_int a and mp_digit b
Output. $c = a^b$

1. $g \leftarrow a$ (*mp_init_copy*)
2. $c \leftarrow 1$ (*mp_set*)
3. for x from 1 to $lg(\beta)$ do
 - 3.1 $c \leftarrow c^2$ (*mp_sqr*)
 - 3.2 If b AND $2^{lg(\beta)-1} \neq 0$ then
 - 3.2.1 $c \leftarrow c \cdot g$ (*mp_mul*)
 - 3.3 $b \leftarrow b \ll 1$
4. Clear g .
5. Return(*MP_OKAY*).

Figure 7.3: Algorithm mp_expt_d

Algorithm mp_expt_d. This algorithm computes the value of a raised to the power of a single digit b . It uses the left to right exponentiation algorithm to quickly compute the exponentiation. It is loosely based on algorithm 14.79 of HAC [2, pp. 615] with the difference that the exponent is a fixed width.

A copy of a is made first to allow destination variable c be the same as the source variable a . The result is set to the initial value of 1 in the subsequent step.

Inside the loop the exponent is read from the most significant bit first down to the least significant bit. First c is invariably squared on step 3.1. In the following step if the most significant bit of b is one the copy of a is multiplied against c . The value of b is shifted left one bit to make the next bit down from the most significant bit the new most significant bit. In effect each iteration of the loop moves the bits of the exponent b upwards to the most significant location.

File: bn_mp_expt_d.c

```

016
017  /* calculate c = a**b using a square-multiply algorithm */
018  int mp_expt_d (mp_int * a, mp_digit b, mp_int * c)
019  {
020      int      res, x;
021      mp_int  g;
022
023      if ((res = mp_init_copy (&g, a)) != MP_OKAY) {

```

```

024     return res;
025 }
026
027 /* set initial result */
028 mp_set (c, 1);
029
030 for (x = 0; x < (int) DIGIT_BIT; x++) {
031     /* square */
032     if ((res = mp_sqr (c, c)) != MP_OKAY) {
033         mp_clear (&g);
034         return res;
035     }
036
037     /* if the bit is set multiply */
038     if ((b & (mp_digit) (((mp_digit)1) << (DIGIT_BIT - 1))) != 0) {
039         if ((res = mp_mul (c, &g, c)) != MP_OKAY) {
040             mp_clear (&g);
041             return res;
042         }
043     }
044
045     /* shift to next bit */
046     b <<= 1;
047 }
048
049 mp_clear (&g);
050 return MP_OKAY;
051 }

```

Line 28 sets the initial value of the result to 1. Next the loop on line 30 steps through each bit of the exponent starting from the most significant down towards the least significant. The invariant squaring operation placed on line 32 is performed first. After the squaring the result c is multiplied by the base g if and only if the most significant bit of the exponent is set. The shift on line 46 moves all of the bits of the exponent upwards towards the most significant location.

7.2 k -ary Exponentiation

When calculating an exponentiation the most time consuming bottleneck is the multiplications which are in general a small factor slower than squaring. Recall

from the previous algorithm that b_i refers to the i 'th bit of the exponent b . Suppose instead it referred to the i 'th k -bit digit of the exponent of b . For $k = 1$ the definitions are synonymous and for $k > 1$ algorithm 7.4 computes the same exponentiation. A group of k bits from the exponent is called a *window*. That is it is a small window on only a portion of the entire exponent. Consider the following modification to the basic left to right exponentiation algorithm.

Algorithm k -ary Exponentiation.

Input. Integer a, b, k and t

Output. $c = a^b$

1. $c \leftarrow 1$
 2. for i from $t - 1$ to 0 do
 - 2.1 $c \leftarrow c^{2^k}$
 - 2.2 Extract the i 'th k -bit word from b and store it in g .
 - 2.3 $c \leftarrow c \cdot a^g$
 3. Return c .
-

Figure 7.4: k -ary Exponentiation

The squaring on step 2.1 can be calculated by squaring the value c successively k times. If the values of a^g for $0 < g < 2^k$ have been precomputed this algorithm requires only t multiplications and tk squarings. The table can be generated with $2^{k-1} - 1$ squarings and $2^{k-1} + 1$ multiplications. This algorithm assumes that the number of bits in the exponent is evenly divisible by k . However, when it is not the remaining $0 < x \leq k - 1$ bits can be handled with algorithm 7.1.

Suppose $k = 4$ and $t = 100$. This modified algorithm will require 109 multiplications and 408 squarings to compute the exponentiation. The original algorithm would on average have required 200 multiplications and 400 squarings to compute the same value. The total number of squarings has increased slightly but the number of multiplications has nearly halved.

7.2.1 Optimal Values of k

An optimal value of k will minimize $2^k + \lceil n/k \rceil + n - 1$ for a fixed number of bits in the exponent n . The simplest approach is to brute force search amongst the values $k = 2, 3, \dots, 8$ for the lowest result. Table 7.5 lists optimal values of k for various exponent sizes and compares the number of multiplication and

squarings required against algorithm 7.1.

Exponent (bits)	Optimal k	Work at k	Work with 7.1
16	2	27	24
32	3	49	48
64	3	92	96
128	4	175	192
256	4	335	384
512	5	645	768
1024	6	1257	1536
2048	6	2452	3072
4096	7	4808	6144

Figure 7.5: Optimal Values of k for k -ary Exponentiation

7.2.2 Sliding-Window Exponentiation

A simple modification to the previous algorithm is only generate the upper half of the table in the range $2^{k-1} \leq g < 2^k$. Essentially this is a table for all values of g where the most significant bit of g is a one. However, in order for this to be allowed in the algorithm values of g in the range $0 \leq g < 2^{k-1}$ must be avoided.

Table 7.6 lists optimal values of k for various exponent sizes and compares the work required against algorithm 7.4.

Exponent (bits)	Optimal k	Work at k	Work with 7.4
16	3	24	27
32	3	45	49
64	4	87	92
128	4	167	175
256	5	322	335
512	6	628	645
1024	6	1225	1257
2048	7	2403	2452
4096	8	4735	4808

Figure 7.6: Optimal Values of k for Sliding Window Exponentiation

Algorithm Sliding Window k -ary Exponentiation.

Input. Integer a , b , k and t

Output. $c = a^b$

1. $c \leftarrow 1$
 2. for i from $t - 1$ to 0 do
 - 2.1 If the i 'th bit of b is a zero then
 - 2.1.1 $c \leftarrow c^2$
 - 2.2 else do
 - 2.2.1 $c \leftarrow c^{2^k}$
 - 2.2.2 Extract the k bits from $(b_i b_{i-1} \dots b_{i-(k-1)})$ and store it in g .
 - 2.2.3 $c \leftarrow c \cdot a^g$
 - 2.2.4 $i \leftarrow i - k$
 3. Return c .
-

Figure 7.7: Sliding Window k -ary Exponentiation

Similar to the previous algorithm this algorithm must have a special handler when fewer than k bits are left in the exponent. While this algorithm requires the same number of squarings it can potentially have fewer multiplications. The pre-computed table a^g is also half the size as the previous table.

Consider the exponent $b = 111101011001000_2 \equiv 31432_{10}$ with $k = 3$ using both algorithms. The first algorithm will divide the exponent up as the following five 3-bit words $b \equiv (111, 101, 011, 001, 000)_2$. The second algorithm will break the exponent as $b \equiv (111, 101, 0, 110, 0, 100, 0)_2$. The single digit 0 in the second representation are where a single squaring took place instead of a squaring and multiplication. In total the first method requires 10 multiplications and 18 squarings. The second method requires 8 multiplications and 18 squarings.

In general the sliding window method is never slower than the generic k -ary method and often it is slightly faster.

7.3 Modular Exponentiation

Modular exponentiation is essentially computing the power of a base within a finite field or ring. For example, computing $d \equiv a^b \pmod{c}$ is a modular exponentiation. Instead of first computing a^b and then reducing it modulo c the intermediate result is reduced modulo c after every squaring or multiplication operation.

This guarantees that any intermediate result is bounded by $0 \leq d \leq c^2 - 2c + 1$ and can be reduced modulo c quickly using one of the algorithms presented in chapter six.

Before the actual modular exponentiation algorithm can be written a wrapper algorithm must be written first. This algorithm will allow the exponent b to be negative which is computed as $c \equiv (1/a)^{|b|} \pmod{d}$. The value of $(1/a) \pmod{c}$ is computed using the modular inverse (see ??). If no inverse exists the algorithm terminates with an error.

Algorithm **mp_exptmod**.
Input. mp_int a , b and c
Output. $y \equiv g^x \pmod{p}$

1. If $c.sign = MP_NEG$ return(MP_VAL).
2. If $b.sign = MP_NEG$ then
 - 2.1 $g' \leftarrow g^{-1} \pmod{c}$
 - 2.2 $x' \leftarrow |x|$
 - 2.3 Compute $d \equiv g^{x'} \pmod{c}$ via recursion.
3. if p is odd **OR** p is a D.R. modulus then
 - 3.1 Compute $y \equiv g^x \pmod{p}$ via algorithm mp_exptmod_fast.
4. else
 - 4.1 Compute $y \equiv g^x \pmod{p}$ via algorithm s_mp_exptmod.

Figure 7.8: Algorithm mp_exptmod

Algorithm mp_exptmod. The first algorithm which actually performs modular exponentiation is algorithm s_mp_exptmod. It is a sliding window k -ary algorithm which uses Barrett reduction to reduce the product modulo p . The second algorithm mp_exptmod_fast performs the same operation except it uses either Montgomery or Diminished Radix reduction. The two latter reduction algorithms are clumped in the same exponentiation algorithm since their arguments are essentially the same (*two mp_ints and one mp_digit*).

File: bn_mp_exptmod.c

```

016
017
018 /* this is a shell function that calls either the normal or Montgomery
019  * exptmod functions. Originally the call to the montgomery code was
020  * embedded in the normal function but that wasted alot of stack space
021  * for nothing (since 99% of the time the Montgomery code would be called)

```

```

022  */
023  int mp_exptmod (mp_int * G, mp_int * X, mp_int * P, mp_int * Y)
024  {
025      int dr;
026
027      /* modulus P must be positive */
028      if (P->sign == MP_NEG) {
029          return MP_VAL;
030      }
031
032      /* if exponent X is negative we have to recurse */
033      if (X->sign == MP_NEG) {
034          mp_int tmpG, tmpX;
035          int err;
036
037          /* first compute 1/G mod P */
038          if ((err = mp_init(&tmpG)) != MP_OKAY) {
039              return err;
040          }
041          if ((err = mp_invmod(G, P, &tmpG)) != MP_OKAY) {
042              mp_clear(&tmpG);
043              return err;
044          }
045
046          /* now get |X| */
047          if ((err = mp_init(&tmpX)) != MP_OKAY) {
048              mp_clear(&tmpG);
049              return err;
050          }
051          if ((err = mp_abs(X, &tmpX)) != MP_OKAY) {
052              mp_clear_multi(&tmpG, &tmpX, NULL);
053              return err;
054          }
055
056          /* and now compute (1/G)**|X| instead of G**X [X < 0] */
057          err = mp_exptmod(&tmpG, &tmpX, P, Y);
058          mp_clear_multi(&tmpG, &tmpX, NULL);
059          return err;
060      }
061
062      /* is it a DR modulus? */
063      dr = mp_dr_is_modulus(P);

```

```

064
065     /* if not, is it a uDR modulus? */
066     if (dr == 0) {
067         dr = mp_reduce_is_2k(P) << 1;
068     }
069
070     /* if the modulus is odd or dr != 0 use the fast method */
071     if (mp_isodd (P) == 1 || dr != 0) {
072         return mp_exptmod_fast (G, X, P, Y, dr);
073     } else {
074         /* otherwise use the generic Barrett reduction technique */
075         return s_mp_exptmod (G, X, P, Y);
076     }
077 }
078

```

In order to keep the algorithms in a known state the first step on line 28 is to reject any negative modulus as input. If the exponent is negative the algorithm tries to perform a modular exponentiation with the modular inverse of the base G . The temporary variable $tmpG$ is assigned the modular inverse of G and $tmpX$ is assigned the absolute value of X . The algorithm will recurse with these new values with a positive exponent.

If the exponent is positive the algorithm resumes the exponentiation. Line 63 determines if the modulus is of the restricted Diminished Radix form. If it is not line 67 attempts to determine if it is of a unrestricted Diminished Radix form. The integer dr will take on one of three values.

1. $dr = 0$ means that the modulus is not of either restricted or unrestricted Diminished Radix form.
2. $dr = 1$ means that the modulus is of restricted Diminished Radix form.
3. $dr = 2$ means that the modulus is of unrestricted Diminished Radix form.

Line 70 determines if the fast modular exponentiation algorithm can be used. It is allowed if $dr \neq 0$ or if the modulus is odd. Otherwise, the slower `s_mp_exptmod` algorithm is used which uses Barrett reduction.

7.3.1 Barrett Modular Exponentiation

Algorithm **s_mp_exptmod**.

Input. mp_int a , b and c

Output. $y \equiv g^x \pmod{p}$

1. $k \leftarrow \lg(x)$
2. $win\ size \leftarrow \begin{cases} 2 & \text{if } k \leq 7 \\ 3 & \text{if } 7 < k \leq 36 \\ 4 & \text{if } 36 < k \leq 140 \\ 5 & \text{if } 140 < k \leq 450 \\ 6 & \text{if } 450 < k \leq 1303 \\ 7 & \text{if } 1303 < k \leq 3529 \\ 8 & \text{if } 3529 < k \end{cases}$
3. Initialize $2^{win\ size}$ mp_ints in an array named M and one mp_int named μ
4. Calculate the μ required for Barrett Reduction (*mp_reduce_setup*).
5. $M_1 \leftarrow g \pmod{p}$

Setup the table of small powers of g . First find $g^{2^{win\ size}}$ and then all multiples of it.

6. $k \leftarrow 2^{win\ size-1}$
7. $M_k \leftarrow M_1$
8. for ix from 0 to $win\ size - 2$ do
 - 8.1 $M_k \leftarrow (M_k)^2$ (*mp_sqr*)
 - 8.2 $M_k \leftarrow M_k \pmod{p}$ (*mp_reduce*)
9. for ix from $2^{win\ size-1} + 1$ to $2^{win\ size} - 1$ do
 - 9.1 $M_{ix} \leftarrow M_{ix-1} \cdot M_1$ (*mp_mul*)
 - 9.2 $M_{ix} \leftarrow M_{ix} \pmod{p}$ (*mp_reduce*)
10. $res \leftarrow 1$

Start Sliding Window.

11. $mode \leftarrow 0, bitcnt \leftarrow 1, buf \leftarrow 0, digidx \leftarrow x.used - 1, bitcpy \leftarrow 0, bitbuf \leftarrow 0$
12. Loop
 - 12.1 $bitcnt \leftarrow bitcnt - 1$
 - 12.2 If $bitcnt = 0$ then do
 - 12.2.1 If $digidx = -1$ goto step 13.
 - 12.2.2 $buf \leftarrow x_{digidx}$
 - 12.2.3 $digidx \leftarrow digidx - 1$
 - 12.2.4 $bitcnt \leftarrow \lg(\beta)$

Continued on next page.

Figure 7.9: Algorithm s_mp_exptmod

Algorithm **s_mp_exptmod** (*continued*).

Input. mp_int a , b and c

Output. $y \equiv g^x \pmod{p}$

12.3 $y \leftarrow (buf \gg (\lg(\beta) - 1)) \text{ AND } 1$
 12.4 $buf \leftarrow buf \lll 1$
 12.5 if $mode = 0$ and $y = 0$ then goto step 12.
 12.6 if $mode = 1$ and $y = 0$ then do
 12.6.1 $res \leftarrow res^2$
 12.6.2 $res \leftarrow res \pmod{p}$
 12.6.3 Goto step 12.
 12.7 $bitcpy \leftarrow bitcpy + 1$
 12.8 $bitbuf \leftarrow bitbuf + (y \lll (winsize - bitcpy))$
 12.9 $mode \leftarrow 2$
 12.10 If $bitcpy = winsize$ then do
 Window is full so perform the squarings and single multiplication.
 12.10.1 for ix from 0 to $winsize - 1$ do
 12.10.1.1 $res \leftarrow res^2$
 12.10.1.2 $res \leftarrow res \pmod{p}$
 12.10.2 $res \leftarrow res \cdot M_{bitbuf}$
 12.10.3 $res \leftarrow res \pmod{p}$
 Reset the window.
 12.10.4 $bitcpy \leftarrow 0, bitbuf \leftarrow 0, mode \leftarrow 1$

 No more windows left. Check for residual bits of exponent.
 13. If $mode = 2$ and $bitcpy > 0$ then do
 13.1 for ix from 0 to $bitcpy - 1$ do
 13.1.1 $res \leftarrow res^2$
 13.1.2 $res \leftarrow res \pmod{p}$
 13.1.3 $bitbuf \leftarrow bitbuf \lll 1$
 13.1.4 If $bitbuf \text{ AND } 2^{winsize} \neq 0$ then do
 13.1.4.1 $res \leftarrow res \cdot M_1$
 13.1.4.2 $res \leftarrow res \pmod{p}$
 14. $y \leftarrow res$
 15. Clear res , mu and the M array.
 16. Return(MP_OKAY).

Figure 7.10: Algorithm s_mp_exptmod (continued)

Algorithm s_mp_exptmod. This algorithm computes the x 'th power of g modulo p and stores the result in y . It takes advantage of the Barrett reduction

algorithm to keep the product small throughout the algorithm.

The first two steps determine the optimal window size based on the number of bits in the exponent. The larger the exponent the larger the window size becomes. After a window size $winsize$ has been chosen an array of $2^{winsize}$ mp_int variables is allocated. This table will hold the values of $g^x \pmod{p}$ for $2^{winsize-1} \leq x < 2^{winsize}$.

After the table is allocated the first power of g is found. Since $g \geq p$ is allowed it must be first reduced modulo p to make the rest of the algorithm more efficient. The first element of the table at $2^{winsize-1}$ is found by squaring M_1 successively $winsize - 2$ times. The rest of the table elements are found by multiplying the previous element by M_1 modulo p .

Now that the table is available the sliding window may begin. The following list describes the functions of all the variables in the window.

1. The variable *mode* dictates how the bits of the exponent are interpreted.
 - (a) When $mode = 0$ the bits are ignored since no non-zero bit of the exponent has been seen yet. For example, if the exponent were simply 1 then there would be $lg(\beta) - 1$ zero bits before the first non-zero bit. In this case bits are ignored until a non-zero bit is found.
 - (b) When $mode = 1$ a non-zero bit has been seen before and a new $winsize$ -bit window has not been formed yet. In this mode leading 0 bits are read and a single squaring is performed. If a non-zero bit is read a new window is created.
 - (c) When $mode = 2$ the algorithm is in the middle of forming a window and new bits are appended to the window from the most significant bit downwards.
2. The variable *bitcnt* indicates how many bits are left in the current digit of the exponent left to be read. When it reaches zero a new digit is fetched from the exponent.
3. The variable *buf* holds the currently read digit of the exponent.
4. The variable *digidx* is an index into the exponents digits. It starts at the leading digit $x.used - 1$ and moves towards the trailing digit.
5. The variable *bitcpy* indicates how many bits are in the currently formed window. When it reaches $winsize$ the window is flushed and the appropriate operations performed.

6. The variable *bitbuf* holds the current bits of the window being formed.

All of step 12 is the window processing loop. It will iterate while there are digits available from the exponent to read. The first step inside this loop is to extract a new digit if no more bits are available in the current digit. If there are no bits left a new digit is read and if there are no digits left than the loop terminates.

After a digit is made available step 12.3 will extract the most significant bit of the current digit and move all other bits in the digit upwards. In effect the digit is read from most significant bit to least significant bit and since the digits are read from leading to trailing edges the entire exponent is read from most significant bit to least significant bit.

At step 12.5 if the *mode* and currently extracted bit *y* are both zero the bit is ignored and the next bit is read. This prevents the algorithm from having to perform trivial squaring and reduction operations before the first non-zero bit is read. Step 12.6 and 12.7-10 handle the two cases of *mode* = 1 and *mode* = 2 respectively.

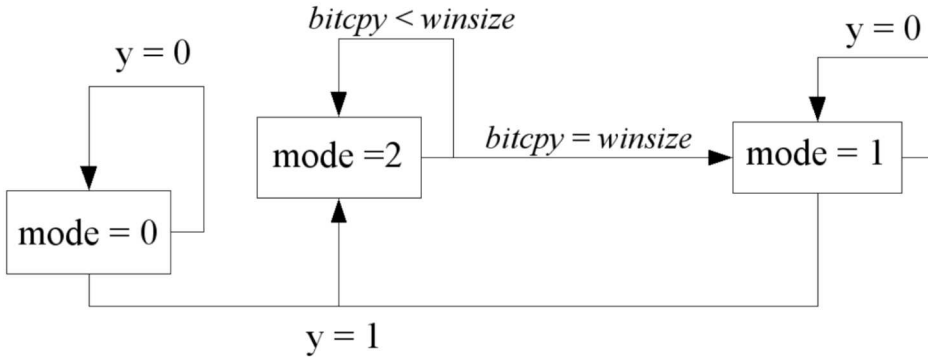


Figure 7.11: Sliding Window State Diagram

By step 13 there are no more digits left in the exponent. However, there may be partial bits in the window left. If *mode* = 2 then a Left-to-Right algorithm is used to process the remaining few bits.

File: bn_s_mp_exptmod.c

```
016
017 #ifdef MP_LOW_MEM
018     #define TAB_SIZE 32
019 #else
020     #define TAB_SIZE 256
021 #endif
022
023 int s_mp_exptmod (mp_int * G, mp_int * X, mp_int * P, mp_int * Y)
024 {
025     mp_int  M[TAB_SIZE], res, mu;
026     mp_digit buf;
027     int     err, bitbuf, bitcpy, bitcnt, mode, digidx, x, y, winsize;
028
029     /* find window size */
030     x = mp_count_bits (X);
031     if (x <= 7) {
032         winsize = 2;
033     } else if (x <= 36) {
034         winsize = 3;
035     } else if (x <= 140) {
036         winsize = 4;
037     } else if (x <= 450) {
038         winsize = 5;
039     } else if (x <= 1303) {
040         winsize = 6;
041     } else if (x <= 3529) {
042         winsize = 7;
043     } else {
044         winsize = 8;
045     }
046
047 #ifdef MP_LOW_MEM
048     if (winsize > 5) {
049         winsize = 5;
050     }
051 #endif
052
053     /* init M array */
054     /* init first cell */
055     if ((err = mp_init(&M[1])) != MP_OKAY) {
056         return err;
057     }
```



```

058
059  /* now init the second half of the array */
060  for (x = 1<<(winsize-1); x < (1 << winsize); x++) {
061      if ((err = mp_init(&M[x])) != MP_OKAY) {
062          for (y = 1<<(winsize-1); y < x; y++) {
063              mp_clear (&M[y]);
064          }
065          mp_clear(&M[1]);
066          return err;
067      }
068  }
069
070  /* create mu, used for Barrett reduction */
071  if ((err = mp_init (&mu)) != MP_OKAY) {
072      goto __M;
073  }
074  if ((err = mp_reduce_setup (&mu, P)) != MP_OKAY) {
075      goto __MU;
076  }
077
078  /* create M table
079  *
080  * The M table contains powers of the base,
081  * e.g. M[x] = G**x mod P
082  *
083  * The first half of the table is not
084  * computed though accept for M[0] and M[1]
085  */
086  if ((err = mp_mod (G, P, &M[1])) != MP_OKAY) {
087      goto __MU;
088  }
089
090  /* compute the value at M[1<<(winsize-1)] by squaring
091  * M[1] (winsize-1) times
092  */
093  if ((err = mp_copy (&M[1], &M[1 << (winsize - 1)])) != MP_OKAY) {
094      goto __MU;
095  }
096
097  for (x = 0; x < (winsize - 1); x++) {
098      if ((err = mp_sqr (&M[1 << (winsize - 1)],
099                      &M[1 << (winsize - 1)])) != MP_OKAY) {

```

```

100     goto __MU;
101     }
102     if ((err = mp_reduce (&M[1 << (winsize - 1)], P, &mu)) != MP_OKAY) {
103         goto __MU;
104     }
105 }
106
107 /* create upper table, that is  $M[x] = M[x-1] * M[1] \pmod{P}$ 
108 * for  $x = (2^{**}(\text{winsize} - 1) + 1)$  to  $(2^{**}\text{winsize} - 1)$ 
109 */
110 for ( $x = (1 << (\text{winsize} - 1)) + 1$ ;  $x < (1 << \text{winsize})$ ;  $x++$ ) {
111     if ((err = mp_mul (&M[x - 1], &M[1], &M[x])) != MP_OKAY) {
112         goto __MU;
113     }
114     if ((err = mp_reduce (&M[x], P, &mu)) != MP_OKAY) {
115         goto __MU;
116     }
117 }
118
119 /* setup result */
120 if ((err = mp_init (&res)) != MP_OKAY) {
121     goto __MU;
122 }
123 mp_set (&res, 1);
124
125 /* set initial mode and bit cnt */
126 mode = 0;
127 bitcnt = 1;
128 buf = 0;
129 digidx = X->used - 1;
130 bitcpy = 0;
131 bitbuf = 0;
132
133 for (;;) {
134     /* grab next digit as required */
135     if (--bitcnt == 0) {
136         /* if digidx == -1 we are out of digits */
137         if (digidx == -1) {
138             break;
139         }
140         /* read next digit and reset the bitcnt */
141         buf = X->dp[digidx--];

```

```

142     bitcnt = (int) DIGIT_BIT;
143     }
144
145     /* grab the next msb from the exponent */
146     y     = (buf >> (mp_digit)(DIGIT_BIT - 1)) & 1;
147     buf <<= (mp_digit)1;
148
149     /* if the bit is zero and mode == 0 then we ignore it
150      * These represent the leading zero bits before the first 1 bit
151      * in the exponent. Technically this opt is not required but it
152      * does lower the # of trivial squaring/reductions used
153      */
154     if (mode == 0 && y == 0) {
155         continue;
156     }
157
158     /* if the bit is zero and mode == 1 then we square */
159     if (mode == 1 && y == 0) {
160         if ((err = mp_sqr (&res, &res)) != MP_OKAY) {
161             goto __RES;
162         }
163         if ((err = mp_reduce (&res, P, &mu)) != MP_OKAY) {
164             goto __RES;
165         }
166         continue;
167     }
168
169     /* else we add it to the window */
170     bitbuf |= (y << (winsize - ++bitcpy));
171     mode     = 2;
172
173     if (bitcpy == winsize) {
174         /* ok window is filled so square as required and multiply */
175         /* square first */
176         for (x = 0; x < winsize; x++) {
177             if ((err = mp_sqr (&res, &res)) != MP_OKAY) {
178                 goto __RES;
179             }
180             if ((err = mp_reduce (&res, P, &mu)) != MP_OKAY) {
181                 goto __RES;
182             }
183         }

```

```

184
185     /* then multiply */
186     if ((err = mp_mul (&res, &M[bitbuf], &res)) != MP_OKAY) {
187         goto __RES;
188     }
189     if ((err = mp_reduce (&res, P, &mu)) != MP_OKAY) {
190         goto __RES;
191     }
192
193     /* empty window and reset */
194     bitcpy = 0;
195     bitbuf = 0;
196     mode = 1;
197 }
198 }
199
200 /* if bits remain then square/multiply */
201 if (mode == 2 && bitcpy > 0) {
202     /* square then multiply if the bit is set */
203     for (x = 0; x < bitcpy; x++) {
204         if ((err = mp_sqr (&res, &res)) != MP_OKAY) {
205             goto __RES;
206         }
207         if ((err = mp_reduce (&res, P, &mu)) != MP_OKAY) {
208             goto __RES;
209         }
210
211         bitbuf <<= 1;
212         if ((bitbuf & (1 << winsize)) != 0) {
213             /* then multiply */
214             if ((err = mp_mul (&res, &M[1], &res)) != MP_OKAY) {
215                 goto __RES;
216             }
217             if ((err = mp_reduce (&res, P, &mu)) != MP_OKAY) {
218                 goto __RES;
219             }
220         }
221     }
222 }
223
224 mp_exch (&res, Y);
225 err = MP_OKAY;

```

```

226  __RES:mp_clear (&res);
227  __MU:mp_clear (&mu);
228  __M:
229      mp_clear(&M[1]);
230      for (x = 1<<(winsize-1); x < (1 << winsize); x++) {
231          mp_clear (&M[x]);
232      }
233      return err;
234  }
```

Lines 31 through 41 determine the optimal window size based on the length of the exponent in bits. The window divisions are sorted from smallest to greatest so that in each `if` statement only one condition must be tested. For example, by the `if` statement on line 33 the value of x is already known to be greater than 140.

The conditional piece of code beginning on line 47 allows the window size to be restricted to five bits. This logic is used to ensure the table of precomputed powers of G remains relatively small.

The for loop on line 60 initializes the M array while lines 61 and 74 compute the value of μ required for Barrett reduction.

– More later.

7.4 Quick Power of Two

Calculating $b = 2^a$ can be performed much quicker than with any of the previous algorithms. Recall that a logical shift left $m \ll k$ is equivalent to $m \cdot 2^k$. By this logic when $m = 1$ a quick power of two can be achieved.

Algorithm **mp_2expt**.

Input. integer b

Output. $a \leftarrow 2^b$

1. $a \leftarrow 0$
 2. If $a.alloc < \lfloor b/lg(\beta) \rfloor + 1$ then grow a appropriately.
 3. $a.used \leftarrow \lfloor b/lg(\beta) \rfloor + 1$
 4. $a_{\lfloor b/lg(\beta) \rfloor} \leftarrow 1 \ll (b \bmod lg(\beta))$
 5. Return(MP_OKAY).
-

Figure 7.12: Algorithm mp_2expt

Algorithm mp_2expt.

File: bn_mp_2expt.c

```
016
017 /* computes a = 2**b
018 *
019 * Simple algorithm which zeroes the int, grows it then just sets one bit
020 * as required.
021 */
022 int
023 mp_2expt (mp_int * a, int b)
024 {
025     int     res;
026
027     /* zero a as per default */
028     mp_zero (a);
029
030     /* grow a to accomodate the single bit */
031     if ((res = mp_grow (a, b / DIGIT_BIT + 1)) != MP_OKAY) {
032         return res;
033     }
034
035     /* set the used count of where the bit will go */
036     a->used = b / DIGIT_BIT + 1;
037
038     /* put the single bit in its place */
039     a->dp[b / DIGIT_BIT] = 1 << (b % DIGIT_BIT);
040
041     return MP_OKAY;
042 }
```

Chapter 8

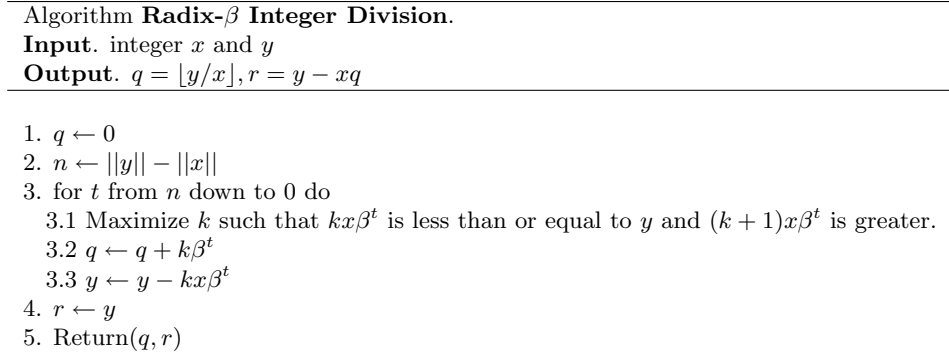
Higher Level Algorithms

This chapter discusses the various higher level algorithms that are required to complete a well rounded multiple precision integer package. These routines are less performance oriented than the algorithms of chapters five, six and seven but are no less important.

The first section describes a method of integer division with remainder that is universally well known. It provides the signed division logic for the package. The subsequent section discusses a set of algorithms which allow a single digit to be the 2nd operand for a variety of operations. These algorithms serve mostly to simplify other algorithms where small constants are required. The last two sections discuss how to manipulate various representations of integers. For example, converting from an `mp_int` to a string of character.

8.1 Integer Division with Remainder

Integer division aside from modular exponentiation is the most intensive algorithm to compute. Like addition, subtraction and multiplication the basis of this algorithm is the long-hand division algorithm taught to school children. Throughout this discussion several common variables will be used. Let x represent the divisor and y represent the dividend. Let q represent the integer quotient $\lfloor y/x \rfloor$ and let r represent the remainder $r = y - x\lfloor y/x \rfloor$. The following simple algorithm will be used to start the discussion.

Figure 8.1: Algorithm Radix- β Integer Division

As children we are taught this very simple algorithm for the case of $\beta = 10$. Almost instinctively several optimizations are taught for which their reason of existing are never explained. For this example let $y = 5471$ represent the dividend and $x = 23$ represent the divisor.

To find the first digit of the quotient the value of k must be maximized such that $kx\beta^t$ is less than or equal to y and simultaneously $(k+1)x\beta^t$ is greater than y . Implicitly k is the maximum value the t 'th digit of the quotient may have. The habitual method used to find the maximum is to “eyeball” the two numbers, typically only the leading digits and quickly estimate a quotient. By only using leading digits a much simpler division may be used to form an educated guess at what the value must be. In this case $k = \lfloor 54/23 \rfloor = 2$ quickly arises as a possible solution. Indeed $2x\beta^2 = 4600$ is less than $y = 5471$ and simultaneously $(k+1)x\beta^2 = 6900$ is larger than y . As a result $k\beta^2$ is added to the quotient which now equals $q = 200$ and 4600 is subtracted from y to give a remainder of $y = 841$.

Again this process is repeated to produce the quotient digit $k = 3$ which makes the quotient $q = 200 + 3\beta = 230$ and the remainder $y = 841 - 3x\beta = 181$. Finally the last iteration of the loop produces $k = 7$ which leads to the quotient $q = 230 + 7 = 237$ and the remainder $y = 181 - 7x = 20$. The final quotient and remainder found are $q = 237$ and $r = y = 20$ which are indeed correct since $237 \cdot 23 + 20 = 5471$ is true.

8.1.1 Quotient Estimation

As alluded to earlier the quotient digit k can be estimated from only the leading digits of both the divisor and dividend. When p leading digits are used from both the divisor and dividend to form an estimation the accuracy of the estimation rises as p grows. Technically speaking the estimation is based on assuming the lower $\|y\| - p$ and $\|x\| - p$ lower digits of the dividend and divisor are zero.

The value of the estimation may off by a few values in either direction and in general is fairly correct. A simplification [1, pp. 271] of the estimation technique is to use $t + 1$ digits of the dividend and t digits of the divisor, in particularly when $t = 1$. The estimate using this technique is never too small. For the following proof let $t = \|y\| - 1$ and $s = \|x\| - 1$ represent the most significant digits of the dividend and divisor respectively.

Proof. *The quotient $\hat{k} = \lfloor (y_t\beta + y_{t-1})/x_s \rfloor$ is greater than or equal to $k = \lfloor y/(x \cdot \beta^{\|y\| - \|x\| - 1}) \rfloor$.* The first obvious case is when $\hat{k} = \beta - 1$ in which case the proof is concluded since the real quotient cannot be larger. For all other cases $\hat{k} = \lfloor (y_t\beta + y_{t-1})/x_s \rfloor$ and $\hat{k}x_s \geq y_t\beta + y_{t-1} - x_s + 1$. The latter portion of the inequality $-x_s + 1$ arises from the fact that a truncated integer division will give the same quotient for at most $x_s - 1$ values. Next a series of inequalities will prove the hypothesis.

$$y - \hat{k}x \leq y - \hat{k}x_s\beta^s \quad (8.1)$$

This is trivially true since $x \geq x_s\beta^s$. Next we replace $\hat{k}x_s\beta^s$ by the previous inequality for $\hat{k}x_s$.

$$y - \hat{k}x \leq y_t\beta^t + \dots + y_0 - (y_t\beta^t + y_{t-1}\beta^{t-1} - x_s\beta^t + \beta^s) \quad (8.2)$$

By simplifying the previous inequality the following inequality is formed.

$$y - \hat{k}x \leq y_{t-2}\beta^{t-2} + \dots + y_0 + x_s\beta^s - \beta^s \quad (8.3)$$

Subsequently,

$$y_{t-2}\beta^{t-2} + \dots + y_0 + x_s\beta^s - \beta^s < x_s\beta^s \leq x \quad (8.4)$$

Which proves that $y - \hat{k}x \leq x$ and by consequence $\hat{k} \geq k$ which concludes the proof. **QED**

8.1.2 Normalized Integers

For the purposes of division a normalized input is when the divisors leading digit x_n is greater than or equal to $\beta/2$. By multiplying both x and y by $j = \lfloor (\beta/2)/x_n \rfloor$ the quotient remains unchanged and the remainder is simply j times the original remainder. The purpose of normalization is to ensure the leading digit of the divisor is sufficiently large such that the estimated quotient will lie in the domain of a single digit. Consider the maximum dividend $(\beta - 1) \cdot \beta + (\beta - 1)$ and the minimum divisor $\beta/2$.

$$\frac{\beta^2 - 1}{\beta/2} \leq 2\beta - \frac{2}{\beta} \quad (8.5)$$

At most the quotient approaches 2β , however, in practice this will not occur since that would imply the previous quotient digit was too small.

8.1.3 Radix- β Division with Remainder

Algorithm **mp.div**.

Input. mp_int a, b

Output. $c = \lfloor a/b \rfloor, d = a - bc$

1. If $b = 0$ return(*MP_VAL*).
2. If $|a| < |b|$ then do
 - 2.1 $d \leftarrow a$
 - 2.2 $c \leftarrow 0$
 - 2.3 Return(*MP_OKAY*).

Setup the quotient to receive the digits.

3. Grow q to $a.used + 2$ digits.
4. $q \leftarrow 0$
5. $x \leftarrow |a|, y \leftarrow |b|$
6. $sign \leftarrow \begin{cases} MP_ZPOS & \text{if } a.sign = b.sign \\ MP_NEG & \text{otherwise} \end{cases}$

Normalize the inputs such that the leading digit of y is greater than or equal to $\beta/2$.

7. $norm \leftarrow (lg(\beta) - 1) - (\lceil lg(y) \rceil \pmod{lg(\beta)})$
8. $x \leftarrow x \cdot 2^{norm}, y \leftarrow y \cdot 2^{norm}$

Find the leading digit of the quotient.

9. $n \leftarrow x.used - 1, t \leftarrow y.used - 1$
10. $y \leftarrow y \cdot \beta^{n-t}$
11. While $(x \geq y)$ do
 - 11.1 $q_{n-t} \leftarrow q_{n-t} + 1$
 - 11.2 $x \leftarrow x - y$
12. $y \leftarrow \lfloor y/\beta^{n-t} \rfloor$

Continued on the next page.

Figure 8.2: Algorithm mp.div

Algorithm **mp_div** (continued).

Input. mp_int a, b

Output. $c = \lfloor a/b \rfloor, d = a - bc$

Now find the remainder for the digits.

13. for i from n down to $(t + 1)$ do
 - 13.1 If $i > x.used$ then jump to the next iteration of this loop.
 - 13.2 If $x_i = y_t$ then
 - 13.2.1 $q_{i-t-1} \leftarrow \beta - 1$
 - 13.3 else
 - 13.3.1 $\hat{r} \leftarrow x_i \cdot \beta + x_{i-1}$
 - 13.3.2 $\hat{r} \leftarrow \lfloor \hat{r}/y_t \rfloor$
 - 13.3.3 $q_{i-t-1} \leftarrow \hat{r}$
 - 13.4 $q_{i-t-1} \leftarrow q_{i-t-1} + 1$

Fixup quotient estimation.

- 13.5 Loop
 - 13.5.1 $q_{i-t-1} \leftarrow q_{i-t-1} - 1$
 - 13.5.2 $t1 \leftarrow 0$
 - 13.5.3 $t1_0 \leftarrow y_{t-1}, t1_1 \leftarrow y_t, t1.used \leftarrow 2$
 - 13.5.4 $t1 \leftarrow t1 \cdot q_{i-t-1}$
 - 13.5.5 $t2_0 \leftarrow x_{i-2}, t2_1 \leftarrow x_{i-1}, t2_2 \leftarrow x_i, t2.used \leftarrow 3$
 - 13.5.6 If $|t1| > |t2|$ then goto step 13.5.
- 13.6 $t1 \leftarrow y \cdot q_{i-t-1}$
- 13.7 $t1 \leftarrow t1 \cdot \beta^{i-t-1}$
- 13.8 $x \leftarrow x - t1$
- 13.9 If $x.sign = MP_NEG$ then
 - 13.10 $t1 \leftarrow y$
 - 13.11 $t1 \leftarrow t1 \cdot \beta^{i-t-1}$
 - 13.12 $x \leftarrow x + t1$
 - 13.13 $q_{i-t-1} \leftarrow q_{i-t-1} - 1$

Finalize the result.

14. Clamp excess digits of q
 15. $c \leftarrow q, c.sign \leftarrow sign$
 16. $x.sign \leftarrow a.sign$
 17. $d \leftarrow \lfloor x/2^{norm} \rfloor$
 18. Return(MP_OKAY).
-

Figure 8.3: Algorithm mp_div (continued)

Algorithm mp_div. This algorithm will calculate quotient and remainder from an integer division given a dividend and divisor. The algorithm is a signed division and will produce a fully qualified quotient and remainder.

First the divisor b must be non-zero which is enforced in step one. If the divisor is larger than the dividend than the quotient is implicitly zero and the remainder is the dividend.

After the first two trivial cases of inputs are handled the variable q is setup to receive the digits of the quotient. Two unsigned copies of the divisor y and dividend x are made as well. The core of the division algorithm is an unsigned division and will only work if the values are positive. Now the two values x and y must be normalized such that the leading digit of y is greater than or equal to $\beta/2$. This is performed by shifting both to the left by enough bits to get the desired normalization.

At this point the division algorithm can begin producing digits of the quotient. Recall that maximum value of the estimation used is $2\beta - \frac{2}{\beta}$ which means that a digit of the quotient must be first produced by another means. In this case y is shifted to the left (*step ten*) so that it has the same number of digits as x . The loop on step eleven will subtract multiples of the shifted copy of y until x is smaller. Since the leading digit of y is greater than or equal to $\beta/2$ this loop will iterate at most two times to produce the desired leading digit of the quotient.

Now the remainder of the digits can be produced. The equation $\hat{q} = \lfloor \frac{x_i\beta + x_{i-1}}{y_t} \rfloor$ is used to fairly accurately approximate the true quotient digit. The estimation can in theory produce an estimation as high as $2\beta - \frac{2}{\beta}$ but by induction the upper quotient digit is correct (*as established on step eleven*) and the estimate must be less than β .

Recall from section 8.1.1 that the estimation is never too low but may be too high. The next step of the estimation process is to refine the estimation. The loop on step 13.5 uses $x_i\beta^2 + x_{i-1}\beta + x_{i-2}$ and $q_{i-t-1}(y_t\beta + y_{t-1})$ as a higher order approximation to adjust the quotient digit.

After both phases of estimation the quotient digit may still be off by a value of one¹. Steps 13.6 and 13.7 subtract the multiple of the divisor from the dividend (*Similar to step 3.3 of algorithm 8.1*) and then subsequently add a multiple of the divisor if the quotient was too large.

Now that the quotient has been determine finalizing the result is a matter of clamping the quotient, fixing the sizes and de-normalizing the remainder. An important aspect of this algorithm seemingly overlooked in other descriptions

¹This is similar to the error introduced by optimizing Barrett reduction.

such as that of Algorithm 14.20 HAC [2, pp. 598] is that when the estimations are being made (*inside the loop on step 13.5*) that the digits y_{t-1} , x_{i-2} and x_{i-1} may lie outside their respective boundaries. For example, if $t = 0$ or $i \leq 1$ then the digits would be undefined. In those cases the digits should respectively be replaced with a zero.

File: bn_mp_div.c

```

016
017 /* integer signed division.
018 * c*b + d == a [e.g. a/b, c=quotient, d=remainder]
019 * HAC pp.598 Algorithm 14.20
020 *
021 * Note that the description in HAC is horribly
022 * incomplete. For example, it doesn't consider
023 * the case where digits are removed from 'x' in
024 * the inner loop. It also doesn't consider the
025 * case that y has fewer than three digits, etc..
026 *
027 * The overall algorithm is as described as
028 * 14.20 from HAC but fixed to treat these cases.
029 */
030 int mp_div (mp_int * a, mp_int * b, mp_int * c, mp_int * d)
031 {
032     mp_int q, x, y, t1, t2;
033     int res, n, t, i, norm, neg;
034
035     /* is divisor zero ? */
036     if (mp_iszero (b) == 1) {
037         return MP_VAL;
038     }
039
040     /* if a < b then q=0, r = a */
041     if (mp_cmp_mag (a, b) == MP_LT) {
042         if (d != NULL) {
043             res = mp_copy (a, d);
044         } else {
045             res = MP_OKAY;
046         }
047         if (c != NULL) {
048             mp_zero (c);
049         }
050         return res;

```

```

051     }
052
053     if ((res = mp_init_size (&q, a->used + 2)) != MP_OKAY) {
054         return res;
055     }
056     q.used = a->used + 2;
057
058     if ((res = mp_init (&t1)) != MP_OKAY) {
059         goto __Q;
060     }
061
062     if ((res = mp_init (&t2)) != MP_OKAY) {
063         goto __T1;
064     }
065
066     if ((res = mp_init_copy (&x, a)) != MP_OKAY) {
067         goto __T2;
068     }
069
070     if ((res = mp_init_copy (&y, b)) != MP_OKAY) {
071         goto __X;
072     }
073
074     /* fix the sign */
075     neg = (a->sign == b->sign) ? MP_ZPOS : MP_NEG;
076     x.sign = y.sign = MP_ZPOS;
077
078     /* normalize both x and y, ensure that y >= b/2, [b == 2**DIGIT_BIT] */
079     norm = mp_count_bits(&y) % DIGIT_BIT;
080     if (norm < (int)(DIGIT_BIT-1)) {
081         norm = (DIGIT_BIT-1) - norm;
082         if ((res = mp_mul_2d (&x, norm, &x)) != MP_OKAY) {
083             goto __Y;
084         }
085         if ((res = mp_mul_2d (&y, norm, &y)) != MP_OKAY) {
086             goto __Y;
087         }
088     } else {
089         norm = 0;
090     }
091
092     /* note hac does 0 based, so if used==5 then its 0,1,2,3,4, e.g. use 4 */

```

```

093     n = x.used - 1;
094     t = y.used - 1;
095
096     /* while (x >= y*b**n-t) do { q[n-t] += 1; x -= y*b**{n-t} } */
097     if ((res = mp_lshd (&y, n - t)) != MP_OKAY) { /* y = y*b**{n-t} */
098         goto __Y;
099     }
100
101     while (mp_cmp (&x, &y) != MP_LT) {
102         ++(q.dp[n - t]);
103         if ((res = mp_sub (&x, &y, &x)) != MP_OKAY) {
104             goto __Y;
105         }
106     }
107
108     /* reset y by shifting it back down */
109     mp_rshd (&y, n - t);
110
111     /* step 3. for i from n down to (t + 1) */
112     for (i = n; i >= (t + 1); i--) {
113         if (i > x.used) {
114             continue;
115         }
116
117         /* step 3.1 if xi == yt then set q{i-t-1} to b-1,
118          * otherwise set q{i-t-1} to (xi*b + x{i-1})/yt */
119         if (x.dp[i] == y.dp[t]) {
120             q.dp[i - t - 1] = (((mp_digit)1) << DIGIT_BIT) - 1);
121         } else {
122             mp_word tmp;
123             tmp = ((mp_word) x.dp[i]) << ((mp_word) DIGIT_BIT);
124             tmp |= ((mp_word) x.dp[i - 1]);
125             tmp /= ((mp_word) y.dp[t]);
126             if (tmp > (mp_word) MP_MASK)
127                 tmp = MP_MASK;
128             q.dp[i - t - 1] = (mp_digit) (tmp & (mp_word) (MP_MASK));
129         }
130
131         /* while (q{i-t-1} * (yt * b + y{t-1})) >
132             xi * b**2 + xi-1 * b + xi-2
133
134         do q{i-t-1} -= 1;

```



```

135     */
136     q.dp[i - t - 1] = (q.dp[i - t - 1] + 1) & MP_MASK;
137     do {
138         q.dp[i - t - 1] = (q.dp[i - t - 1] - 1) & MP_MASK;
139
140         /* find left hand */
141         mp_zero (&t1);
142         t1.dp[0] = (t - 1 < 0) ? 0 : y.dp[t - 1];
143         t1.dp[1] = y.dp[t];
144         t1.used = 2;
145         if ((res = mp_mul_d (&t1, q.dp[i - t - 1], &t1)) != MP_OKAY) {
146             goto __Y;
147         }
148
149         /* find right hand */
150         t2.dp[0] = (i - 2 < 0) ? 0 : x.dp[i - 2];
151         t2.dp[1] = (i - 1 < 0) ? 0 : x.dp[i - 1];
152         t2.dp[2] = x.dp[i];
153         t2.used = 3;
154     } while (mp_cmp_mag(&t1, &t2) == MP_GT);
155
156     /* step 3.3 x = x - q{i-t-1} * y * b**{i-t-1} */
157     if ((res = mp_mul_d (&y, q.dp[i - t - 1], &t1)) != MP_OKAY) {
158         goto __Y;
159     }
160
161     if ((res = mp_lshd (&t1, i - t - 1)) != MP_OKAY) {
162         goto __Y;
163     }
164
165     if ((res = mp_sub (&x, &t1, &x)) != MP_OKAY) {
166         goto __Y;
167     }
168
169     /* if x < 0 then { x = x + y*b**{i-t-1}; q{i-t-1} -= 1; } */
170     if (x.sign == MP_NEG) {
171         if ((res = mp_copy (&y, &t1)) != MP_OKAY) {
172             goto __Y;
173         }
174         if ((res = mp_lshd (&t1, i - t - 1)) != MP_OKAY) {
175             goto __Y;
176         }

```

```

177     if ((res = mp_add (&x, &t1, &x)) != MP_OKAY) {
178         goto __Y;
179     }
180
181     q.dp[i - t - 1] = (q.dp[i - t - 1] - 1UL) & MP_MASK;
182 }
183 }
184
185 /* now q is the quotient and x is the remainder
186  * [which we have to normalize]
187  */
188
189 /* get sign before writing to c */
190 x.sign = a->sign;
191
192 if (c != NULL) {
193     mp_clamp (&q);
194     mp_exch (&q, c);
195     c->sign = neg;
196 }
197
198 if (d != NULL) {
199     mp_div_2d (&x, norm, &x, NULL);
200     mp_exch (&x, d);
201 }
202
203 res = MP_OKAY;
204
205 __Y:mp_clear (&y);
206 __X:mp_clear (&x);
207 __T2:mp_clear (&t2);
208 __T1:mp_clear (&t1);
209 __Q:mp_clear (&q);
210     return res;
211 }

```

The implementation of this algorithm differs slightly from the pseudo code presented previously. In this algorithm either of the quotient c or remainder d may be passed as a **NULL** pointer which indicates their value is not desired. For example, the C code to call the division algorithm with only the quotient is

```
mp_div(&a, &b, &c, NULL); /* c = [a/b] */
```

Lines 36 and 42 handle the two trivial cases of inputs which are division by zero and dividend smaller than the divisor respectively. After the two trivial cases all of the temporary variables are initialized. Line 75 determines the sign of the quotient and line 76 ensures that both x and y are positive.

The number of bits in the leading digit is calculated on line 80. Implicitly an `mp_int` with r digits will require $lg(\beta)(r - 1) + k$ bits of precision which when reduced modulo $lg(\beta)$ produces the value of k . In this case k is the number of bits in the leading digit which is exactly what is required. For the algorithm to operate k must equal $lg(\beta) - 1$ and when it does not the inputs must be normalized by shifting them to the left by $lg(\beta) - 1 - k$ bits.

Throughout the variables n and t will represent the highest digit of x and y respectively. These are first used to produce the leading digit of the quotient. The loop beginning on line 112 will produce the remainder of the quotient digits.

The conditional “continue” on line 113 is used to prevent the algorithm from reading past the leading edge of x which can occur when the algorithm eliminates multiple non-zero digits in a single iteration. This ensures that x_i is always non-zero since by definition the digits above the i 'th position x must be zero in order for the quotient to be precise².

Lines 142, 143 and 150 through 152 manually construct the high accuracy estimations by setting the digits of the two `mp_int` variables directly.

8.2 Single Digit Helpers

This section briefly describes a series of single digit helper algorithms which come in handy when working with small constants. All of the helper functions assume the single digit input is positive and will treat them as such.

8.2.1 Single Digit Addition and Subtraction

Both addition and subtraction are performed by “cheating” and using `mp_set` followed by the higher level addition or subtraction algorithms. As a result these algorithms are substantially simpler with a slight cost in performance.

²Precise as far as integer division is concerned.

Algorithm **mp_add_d**.
Input. mp_int a and a mp_digit b
Output. $c = a + b$

1. $t \leftarrow b$ (*mp_set*)
2. $c \leftarrow a + t$
3. Return(*MP_OKAY*)

Figure 8.4: Algorithm mp_add_d

Algorithm mp_add_d. This algorithm initiates a temporary mp_int with the value of the single digit and uses algorithm mp_add to add the two values together.

```

File: bn_mp_add_d.c
016
017  /* single digit addition */
018  int
019  mp_add_d (mp_int * a, mp_digit b, mp_int * c)
020  {
021      int      res, ix, oldused;
022      mp_digit *tmpa, *tmpc, mu;
023
024      /* grow c as required */
025      if (c->alloc < a->used + 1) {
026          if ((res = mp_grow(c, a->used + 1)) != MP_OKAY) {
027              return res;
028          }
029      }
030
031      /* if a is negative and |a| >= b, call c = |a| - b */
032      if (a->sign == MP_NEG && (a->used > 1 || a->dp[0] >= b)) {
033          /* temporarily fix sign of a */
034          a->sign = MP_ZPOS;
035
036          /* c = |a| - b */
037          res = mp_sub_d(a, b, c);
038
039          /* fix sign */
040          a->sign = c->sign = MP_NEG;
041
042          return res;

```

```
043     }
044
045     /* old number of used digits in c */
046     oldused = c->used;
047
048     /* sign always positive */
049     c->sign = MP_ZPOS;
050
051     /* source alias */
052     tmpa    = a->dp;
053
054     /* destination alias */
055     tmpc    = c->dp;
056
057     /* if a is positive */
058     if (a->sign == MP_ZPOS) {
059         /* add digit, after this we're propagating
060          * the carry.
061          */
062         *tmpc    = *tmpa++ + b;
063         mu       = *tmpc >> DIGIT_BIT;
064         *tmpc++ &= MP_MASK;
065
066         /* now handle rest of the digits */
067         for (ix = 1; ix < a->used; ix++) {
068             *tmpc    = *tmpa++ + mu;
069             mu       = *tmpc >> DIGIT_BIT;
070             *tmpc++ &= MP_MASK;
071         }
072         /* set final carry */
073         ix++;
074         *tmpc++ = mu;
075
076         /* setup size */
077         c->used = a->used + 1;
078     } else {
079         /* a was negative and |a| < b */
080         c->used = 1;
081
082         /* the result is a single digit */
083         if (a->used == 1) {
084             *tmpc++ = b - a->dp[0];
```

```

085     } else {
086         *tmpc++ = b;
087     }
088
089     /* setup count so the clearing of oldused
090      * can fall through correctly
091      */
092     ix      = 1;
093 }
094
095 /* now zero to oldused */
096 while (ix++ < oldused) {
097     *tmpc++ = 0;
098 }
099 mp_clamp(c);
100
101 return MP_OKAY;
102 }
103

```

Clever use of the letter 't'.

Subtraction

The single digit subtraction algorithm `mp_sub_d` is essentially the same except it uses `mp_sub` to subtract the digit from the `mp_int`.

8.2.2 Single Digit Multiplication

Single digit multiplication arises enough in division and radix conversion that it ought to be implement as a special case of the baseline multiplication algorithm. Essentially this algorithm is a modified version of algorithm `s_mp_mul_digs` where one of the multiplicands only has one digit.

Algorithm `mp_mul_d`. This algorithm quickly multiplies an `mp_int` by a small single digit value. It is specially tailored to the job and has a minimal of overhead. Unlike the full multiplication algorithms this algorithm does not require any significant temporary storage or memory allocations.

File: `bn_mp_mul_d.c`

```

016
017 /* multiply by a digit */
018 int

```

Algorithm **mp_mul_d**.
Input. mp_int a and a mp_digit b
Output. $c = ab$

1. $pa \leftarrow a.used$
2. Grow c to at least $pa + 1$ digits.
3. $oldused \leftarrow c.used$
4. $c.used \leftarrow pa + 1$
5. $c.sign \leftarrow a.sign$
6. $\mu \leftarrow 0$
7. for ix from 0 to $pa - 1$ do
 - 7.1 $\hat{r} \leftarrow \mu + a_{ix}b$
 - 7.2 $c_{ix} \leftarrow \hat{r} \pmod{\beta}$
 - 7.3 $\mu \leftarrow \lfloor \hat{r} / \beta \rfloor$
8. $c_{pa} \leftarrow \mu$
9. for ix from $pa + 1$ to $oldused$ do
 - 9.1 $c_{ix} \leftarrow 0$
10. Clamp excess digits of c .
11. Return(MP_OKAY).

Figure 8.5: Algorithm mp_mul_d

```

019 mp_mul_d (mp_int * a, mp_digit b, mp_int * c)
020 {
021     mp_digit u, *tmpa, *tmpc;
022     mp_word r;
023     int     ix, res, olduse;
024
025     /* make sure c is big enough to hold a*b */
026     if (c->alloc < a->used + 1) {
027         if ((res = mp_grow (c, a->used + 1)) != MP_OKAY) {
028             return res;
029         }
030     }
031
032     /* get the original destinations used count */
033     olduse = c->used;
034
035     /* set the sign */
036     c->sign = a->sign;

```

```

037
038 /* alias for a->dp [source] */
039 tmpa = a->dp;
040
041 /* alias for c->dp [dest] */
042 tmpc = c->dp;
043
044 /* zero carry */
045 u = 0;
046
047 /* compute columns */
048 for (ix = 0; ix < a->used; ix++) {
049     /* compute product and carry sum for this term */
050     r      = ((mp_word) u) + ((mp_word)*tmpa++) * ((mp_word)b);
051
052     /* mask off higher bits to get a single digit */
053     *tmpc++ = (mp_digit) (r & ((mp_word) MP_MASK));
054
055     /* send carry into next iteration */
056     u      = (mp_digit) (r >> ((mp_word) DIGIT_BIT));
057 }
058
059 /* store final carry [if any] */
060 *tmpc++ = u;
061
062 /* now zero digits above the top */
063 while (ix++ < olduse) {
064     *tmpc++ = 0;
065 }
066
067 /* set used count */
068 c->used = a->used + 1;
069 mp_clamp(c);
070
071 return MP_OKAY;
072 }

```

In this implementation the destination *c* may point to the same *mp_int* as the source *a* since the result is written after the digit is read from the source. This function uses pointer aliases *tmpa* and *tmpc* for the digits of *a* and *c* respectively.

8.2.3 Single Digit Division

Like the single digit multiplication algorithm, single digit division is also a fairly common algorithm used in radix conversion. Since the divisor is only a single digit a specialized variant of the division algorithm can be used to compute the quotient.

Algorithm **mp_div_d**.
Input. mp_int a and a mp_digit b
Output. $c = \lfloor a/b \rfloor, d = a - cb$

1. If $b = 0$ then return(*MP_VAL*).
2. If $b = 3$ then use algorithm mp_div_3 instead.
3. Init q to $a.used$ digits.
4. $q.used \leftarrow a.used$
5. $q.sign \leftarrow a.sign$
6. $\hat{w} \leftarrow 0$
7. for ix from $a.used - 1$ down to 0 do
 - 7.1 $\hat{w} \leftarrow \hat{w}\beta + a_{ix}$
 - 7.2 If $\hat{w} \geq b$ then
 - 7.2.1 $t \leftarrow \lfloor \hat{w}/b \rfloor$
 - 7.2.2 $\hat{w} \leftarrow \hat{w} \pmod{b}$
 - 7.3 else
 - 7.3.1 $t \leftarrow 0$
 - 7.4 $q_{ix} \leftarrow t$
8. $d \leftarrow \hat{w}$
9. Clamp excess digits of q .
10. $c \leftarrow q$
11. Return(*MP_OKAY*).

Figure 8.6: Algorithm mp_div_d

Algorithm mp_div_d. This algorithm divides the mp_int a by the single mp_digit b using an optimized approach. Essentially in every iteration of the algorithm another digit of the dividend is reduced and another digit of quotient produced. Provided $b < \beta$ the value of \hat{w} after step 7.1 will be limited such that $0 \leq \lfloor \hat{w}/b \rfloor < \beta$.

If the divisor b is equal to three a variant of this algorithm is used which is called mp_div_3. It replaces the division by three with a multiplication by $\lfloor \beta/3 \rfloor$ and the appropriate shift and residual fixup. In essence it is much like the Barrett reduction from chapter seven.

File: bn_mp_div_d.c

```

016
017 static int s_is_power_of_two(mp_digit b, int *p)
018 {
019     int x;
020
```

```
021     for (x = 1; x < DIGIT_BIT; x++) {
022         if (b == ((mp_digit)1<<x)) {
023             *p = x;
024             return 1;
025         }
026     }
027     return 0;
028 }
029
030 /* single digit division (based on routine from MPI) */
031 int mp_div_d (mp_int * a, mp_digit b, mp_int * c, mp_digit * d)
032 {
033     mp_int q;
034     mp_word w;
035     mp_digit t;
036     int res, ix;
037
038     /* cannot divide by zero */
039     if (b == 0) {
040         return MP_VAL;
041     }
042
043     /* quick outs */
044     if (b == 1 || mp_iszero(a) == 1) {
045         if (d != NULL) {
046             *d = 0;
047         }
048         if (c != NULL) {
049             return mp_copy(a, c);
050         }
051         return MP_OKAY;
052     }
053
054     /* power of two ? */
055     if (s_is_power_of_two(b, &ix) == 1) {
056         if (d != NULL) {
057             *d = a->dp[0] & ((1<<ix) - 1);
058         }
059         if (c != NULL) {
060             return mp_div_2d(a, ix, c, NULL);
061         }
062         return MP_OKAY;
```

```

063     }
064
065     /* three? */
066     if (b == 3) {
067         return mp_div_3(a, c, d);
068     }
069
070     /* no easy answer [c'est la vie]. Just division */
071     if ((res = mp_init_size(&q, a->used)) != MP_OKAY) {
072         return res;
073     }
074
075     q.used = a->used;
076     q.sign = a->sign;
077     w = 0;
078     for (ix = a->used - 1; ix >= 0; ix--) {
079         w = (w << ((mp_word)DIGIT_BIT)) | ((mp_word)a->dp[ix]);
080
081         if (w >= b) {
082             t = (mp_digit)(w / b);
083             w -= ((mp_word)t) * ((mp_word)b);
084         } else {
085             t = 0;
086         }
087         q.dp[ix] = (mp_digit)t;
088     }
089
090     if (d != NULL) {
091         *d = (mp_digit)w;
092     }
093
094     if (c != NULL) {
095         mp_clamp(&q);
096         mp_exch(&q, c);
097     }
098     mp_clear(&q);
099
100     return res;
101 }
102

```

Like the implementation of algorithm `mp_div` this algorithm allows either

of the quotient or remainder to be passed as a **NULL** pointer to indicate the respective value is not required. This allows a trivial single digit modular reduction algorithm, `mp_mod_d` to be created.

The division and remainder on lines 43 and @45,processors can divide a 64-bit quantity by a 32-bit quantity and produce the quotient and remainder simultaneously. Unfortunately the GCC compiler does not recognize that optimization and will actually produce two function calls to find the quotient and remainder respectively.

8.2.4 Single Digit Root Extraction

Finding the n 'th root of an integer is fairly easy as far as numerical analysis is concerned. Algorithms such as the Newton-Raphson approximation (8.6) series will converge very quickly to a root for any continuous function $f(x)$.

$$x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)} \quad (8.6)$$

In this case the n 'th root is desired and $f(x) = x^n - a$ where a is the integer of which the root is desired. The derivative of $f(x)$ is simply $f'(x) = nx^{n-1}$. Of particular importance is that this algorithm will be used over the integers not over the a more continuous domain such as the real numbers. As a result the root found can be above the true root by few and must be manually adjusted. Ideally at the end of the algorithm the n 'th root b of an integer a is desired such that $b^n \leq a$.

Algorithm **mp_n.root**.
Input. mp_int a and a mp_digit b
Output. $c^b \leq a$

1. If b is even and $a.sign = MP_NEG$ return(MP_VAL).
2. $sign \leftarrow a.sign$
3. $a.sign \leftarrow MP_ZPOS$
4. $t2 \leftarrow 2$
5. Loop
 - 5.1 $t1 \leftarrow t2$
 - 5.2 $t3 \leftarrow t1^{b-1}$
 - 5.3 $t2 \leftarrow t3 \cdot t1$
 - 5.4 $t2 \leftarrow t2 - a$
 - 5.5 $t3 \leftarrow t3 \cdot b$
 - 5.6 $t3 \leftarrow \lfloor t2/t3 \rfloor$
 - 5.7 $t2 \leftarrow t1 - t3$
 - 5.8 If $t1 \neq t2$ then goto step 5.
6. Loop
 - 6.1 $t2 \leftarrow t1^b$
 - 6.2 If $t2 > a$ then
 - 6.2.1 $t1 \leftarrow t1 - 1$
 - 6.2.2 Goto step 6.
7. $a.sign \leftarrow sign$
8. $c \leftarrow t1$
9. $c.sign \leftarrow sign$
10. Return(MP_OKAY).

Figure 8.7: Algorithm mp_n.root

Algorithm mp_n.root. This algorithm finds the integer n 'th root of an input using the Newton-Raphson approach. It is partially optimized based on the observation that the numerator of $\frac{f(x)}{f'(x)}$ can be derived from a partial denominator. That is at first the denominator is calculated by finding x^{b-1} . This value can then be multiplied by x and have a subtracted from it to find the numerator. This saves a total of $b - 1$ multiplications by $t1$ inside the loop.

The initial value of the approximation is $t2 = 2$ which allows the algorithm to start with very small values and quickly converge on the root. Ideally this algorithm is meant to find the n 'th root of an input where n is bounded by $2 \leq n \leq 5$.

File: bn_mp_n_root.c

```

016
017 /* find the n'th root of an integer
018  *
019  * Result found such that (c)**b <= a and (c+1)**b > a
020  *
021  * This algorithm uses Newton's approximation
022  * x[i+1] = x[i] - f(x[i])/f'(x[i])
023  * which will find the root in log(N) time where
024  * each step involves a fair bit. This is not meant to
025  * find huge roots [square and cube, etc].
026  */
027 int mp_n_root (mp_int * a, mp_digit b, mp_int * c)
028 {
029     mp_int  t1, t2, t3;
030     int      res, neg;
031
032     /* input must be positive if b is even */
033     if ((b & 1) == 0 && a->sign == MP_NEG) {
034         return MP_VAL;
035     }
036
037     if ((res = mp_init (&t1)) != MP_OKAY) {
038         return res;
039     }
040
041     if ((res = mp_init (&t2)) != MP_OKAY) {
042         goto __T1;
043     }
044
045     if ((res = mp_init (&t3)) != MP_OKAY) {
046         goto __T2;
047     }
048
049     /* if a is negative fudge the sign but keep track */
050     neg      = a->sign;
051     a->sign = MP_ZPOS;
052
053     /* t2 = 2 */
054     mp_set (&t2, 2);
055
056     do {

```

```

057     /* t1 = t2 */
058     if ((res = mp_copy (&t2, &t1)) != MP_OKAY) {
059         goto __T3;
060     }
061
062     /* t2 = t1 - ((t1**b - a) / (b * t1**(b-1))) */
063
064     /* t3 = t1**(b-1) */
065     if ((res = mp_expt_d (&t1, b - 1, &t3)) != MP_OKAY) {
066         goto __T3;
067     }
068
069     /* numerator */
070     /* t2 = t1**b */
071     if ((res = mp_mul (&t3, &t1, &t2)) != MP_OKAY) {
072         goto __T3;
073     }
074
075     /* t2 = t1**b - a */
076     if ((res = mp_sub (&t2, a, &t2)) != MP_OKAY) {
077         goto __T3;
078     }
079
080     /* denominator */
081     /* t3 = t1**(b-1) * b */
082     if ((res = mp_mul_d (&t3, b, &t3)) != MP_OKAY) {
083         goto __T3;
084     }
085
086     /* t3 = (t1**b - a)/(b * t1**(b-1)) */
087     if ((res = mp_div (&t2, &t3, &t3, NULL)) != MP_OKAY) {
088         goto __T3;
089     }
090
091     if ((res = mp_sub (&t1, &t3, &t2)) != MP_OKAY) {
092         goto __T3;
093     }
094 } while (mp_cmp (&t1, &t2) != MP_EQ);
095
096 /* result can be off by a few so check */
097 for (;;) {
098     if ((res = mp_expt_d (&t1, b, &t2)) != MP_OKAY) {

```



```
099     goto __T3;
100     }
101
102     if (mp_cmp (&t2, a) == MP_GT) {
103         if ((res = mp_sub_d (&t1, 1, &t1)) != MP_OKAY) {
104             goto __T3;
105         }
106     } else {
107         break;
108     }
109 }
110
111 /* reset the sign of a first */
112 a->sign = neg;
113
114 /* set the result */
115 mp_exch (&t1, c);
116
117 /* set the sign of the result */
118 c->sign = neg;
119
120 res = MP_OKAY;
121
122 __T3:mp_clear (&t3);
123 __T2:mp_clear (&t2);
124 __T1:mp_clear (&t1);
125     return res;
126 }
```

8.3 Random Number Generation

Random numbers come up in a variety of activities from public key cryptography to simple simulations and various randomized algorithms. Pollard-Rho factoring for example, can make use of random values as starting points to find factors of a composite integer. In this case the algorithm presented is solely for simulations and not intended for cryptographic use.

Algorithm **mp_rand**.

Input. An integer b

Output. A pseudo-random number of b digits

1. $a \leftarrow 0$
 2. If $b \leq 0$ return(*MP_OKAY*)
 3. Pick a non-zero random digit d .
 4. $a \leftarrow a + d$
 5. for ix from 1 to $d - 1$ do
 - 5.1 $a \leftarrow a \cdot \beta$
 - 5.2 Pick a random digit d .
 - 5.3 $a \leftarrow a + d$
 6. Return(*MP_OKAY*).
-

Figure 8.8: Algorithm mp_rand

Algorithm mp_rand. This algorithm produces a pseudo-random integer of b digits. By ensuring that the first digit is non-zero the algorithm also guarantees that the final result has at least b digits. It relies heavily on a third-part random number generator which should ideally generate uniformly all of the integers from 0 to $\beta - 1$.

File: bn_mp_rand.c

```

016
017  /* makes a pseudo-random int of a given size */
018  int
019  mp_rand (mp_int * a, int digits)
020  {
021      int    res;
022      mp_digit d;
023
024      mp_zero (a);
025      if (digits <= 0) {
026          return MP_OKAY;
027      }
028
029      /* first place a random non-zero digit */
030      do {
031          d = ((mp_digit) abs (rand ()));
032      } while (d == 0);
033

```

```
034     if ((res = mp_add_d (a, d, a)) != MP_OKAY) {
035         return res;
036     }
037
038     while (digits-- > 0) {
039         if ((res = mp_lshd (a, 1)) != MP_OKAY) {
040             return res;
041         }
042
043         if ((res = mp_add_d (a, ((mp_digit) abs (rand ())), a)) != MP_OKAY) {
044             return res;
045         }
046     }
047
048     return MP_OKAY;
049 }
```

8.4 Formatted Representations

The ability to emit a radix- n textual representation of an integer is useful for interacting with human parties. For example, the ability to be given a string of characters such as “114585” and turn it into the radix- β equivalent would make it easier to enter numbers into a program.

8.4.1 Reading Radix-n Input

For the purposes of this text we will assume that a simple lower ASCII map (8.9) is used for the values of from 0 to 63 to printable characters. For example, when the character “N” is read it represents the integer 23. The first 16 characters of the map are for the common representations up to hexadecimal. After that they match the “base64” encoding scheme which are suitable chosen such that they are printable. While outputting as base64 may not be too helpful for human operators it does allow communication via non binary mediums.

Value	Char	Value	Char	Value	Char	Value	Char
0	0	1	1	2	2	3	3
4	4	5	5	6	6	7	7
8	8	9	9	10	A	11	B
12	C	13	D	14	E	15	F
16	G	17	H	18	I	19	J
20	K	21	L	22	M	23	N
24	O	25	P	26	Q	27	R
28	S	29	T	30	U	31	V
32	W	33	X	34	Y	35	Z
36	a	37	b	38	c	39	d
40	e	41	f	42	g	43	h
44	i	45	j	46	k	47	l
48	m	49	n	50	o	51	p
52	q	53	r	54	s	55	t
56	u	57	v	58	w	59	x
60	y	61	z	62	+	63	/

Figure 8.9: Lower ASCII Map

Algorithm **mp_read_radix**.

Input. A string *str* of length *sn* and radix *r*.

Output. The radix- β equivalent mp_int.

1. If $r < 2$ or $r > 64$ return(*MP_VAL*).
 2. $ix \leftarrow 0$
 3. If $str_0 = \text{"-"}$ then do
 - 3.1 $ix \leftarrow ix + 1$
 - 3.2 $sign \leftarrow MP_NEG$
 4. else
 - 4.1 $sign \leftarrow MP_ZPOS$
 5. $a \leftarrow 0$
 6. for *iy* from *ix* to *sn* - 1 do
 - 6.1 Let *y* denote the position in the map of str_{iy} .
 - 6.2 If str_{iy} is not in the map or $y \geq r$ then goto step 7.
 - 6.3 $a \leftarrow a \cdot r$
 - 6.4 $a \leftarrow a + y$
 7. If $a \neq 0$ then $a.sign \leftarrow sign$
 8. Return(*MP_OKAY*).
-

Figure 8.10: Algorithm mp_read_radix

Algorithm mp_read_radix. This algorithm will read an ASCII string and produce the radix- β mp_int representation of the same integer. A minus symbol “-” may precede the string to indicate the value is negative, otherwise it is assumed to be positive. The algorithm will read up to *sn* characters from the input and will stop when it reads a character it cannot map the algorithm stops reading characters from the string. This allows numbers to be embedded as part of larger input without any significant problem.

File: bn_mp_read_radix.c

```

016
017  /* read a string [ASCII] in a given radix */
018  int mp_read_radix (mp_int * a, char *str, int radix)
019  {
020      int    y, res, neg;
021      char   ch;
022
023      /* make sure the radix is ok */
024      if (radix < 2 || radix > 64) {
025          return MP_VAL;

```

```

026     }
027
028     /* if the leading digit is a
029     * minus set the sign to negative.
030     */
031     if (*str == '-') {
032         ++str;
033         neg = MP_NEG;
034     } else {
035         neg = MP_ZPOS;
036     }
037
038     /* set the integer to the default of zero */
039     mp_zero (a);
040
041     /* process each digit of the string */
042     while (*str) {
043         /* if the radix < 36 the conversion is case insensitive
044         * this allows numbers like 1AB and 1ab to represent the same value
045         * [e.g. in hex]
046         */
047         ch = (char) ((radix < 36) ? toupper (*str) : *str);
048         for (y = 0; y < 64; y++) {
049             if (ch == mp_s_rmap[y]) {
050                 break;
051             }
052         }
053
054         /* if the char was found in the map
055         * and is less than the given radix add it
056         * to the number, otherwise exit the loop.
057         */
058         if (y < radix) {
059             if ((res = mp_mul_d (a, (mp_digit) radix, a)) != MP_OKAY) {
060                 return res;
061             }
062             if ((res = mp_add_d (a, (mp_digit) y, a)) != MP_OKAY) {
063                 return res;
064             }
065         } else {
066             break;
067         }

```

```
068     ++str;
069   }
070
071   /* set the sign only if a != 0 */
072   if (mp_iszero(a) != 1) {
073     a->sign = neg;
074   }
075   return MP_OKAY;
076 }
```

8.4.2 Generating Radix- n Output

Generating radix- n output is fairly trivial with a division and remainder algorithm.

Algorithm **mp_toradix**.

Input. A mp_int a and an integer r

Output. The radix- r representation of a

1. If $r < 2$ or $r > 64$ return(MP_VAL).
 2. If $a = 0$ then $str = "0"$ and return(MP_OKAY).
 3. $t \leftarrow a$
 4. $str \leftarrow ""$
 5. if $t.sign = MP_NEG$ then
 - 5.1 $str \leftarrow str + "-"$
 - 5.2 $t.sign = MP_ZPOS$
 6. While ($t \neq 0$) do
 - 6.1 $d \leftarrow t \pmod{r}$
 - 6.2 $t \leftarrow \lfloor t/r \rfloor$
 - 6.3 Look up d in the map and store the equivalent character in y .
 - 6.4 $str \leftarrow str + y$
 7. If $str_0 = "-"$ then
 - 7.1 Reverse the digits $str_1, str_2, \dots, str_n$.
 8. Otherwise
 - 8.1 Reverse the digits $str_0, str_1, \dots, str_n$.
 9. Return(MP_OKAY).
-

Figure 8.11: Algorithm mp_toradix

Algorithm mp_toradix. This algorithm computes the radix- r representation of an mp_int a . The “digits” of the representation are extracted by reducing successive powers of $\lfloor a/r^k \rfloor$ the input modulo r until $r^k > a$. Note that instead of actually dividing by r^k in each iteration the quotient $\lfloor a/r \rfloor$ is saved for the next iteration. As a result a series of trivial $n \times 1$ divisions are required instead of a series of $n \times k$ divisions. One design flaw of this approach is that the digits are produced in the reverse order (see 8.12). To remedy this flaw the digits must be swapped or simply “reversed”.

File: bn_mp_toradix.c

```

016
017 /* stores a bignum as a ASCII string in a given radix (2..64) */
018 int mp_toradix (mp_int * a, char *str, int radix)
019 {
020     int     res, digs;
021     mp_int  t;
022     mp_digit d;

```


Value of a	Value of d	Value of str
1234	–	–
123	4	“4”
12	3	“43”
1	2	“432”
0	1	“4321”

Figure 8.12: Example of Algorithm `mp_toradix`.

```

023 char *_s = str;
024
025 /* check range of the radix */
026 if (radix < 2 || radix > 64) {
027     return MP_VAL;
028 }
029
030 /* quick out if its zero */
031 if (mp_iszero(a) == 1) {
032     *str++ = '0';
033     *str = '\0';
034     return MP_OKAY;
035 }
036
037 if ((res = mp_init_copy (&t, a)) != MP_OKAY) {
038     return res;
039 }
040
041 /* if it is negative output a - */
042 if (t.sign == MP_NEG) {
043     ++_s;
044     *str++ = '-';
045     t.sign = MP_ZPOS;
046 }
047
048 digs = 0;
049 while (mp_iszero (&t) == 0) {
050     if ((res = mp_div_d (&t, (mp_digit) radix, &t, &d)) != MP_OKAY) {
051         mp_clear (&t);
052         return res;
053     }

```

```
054     *str++ = mp_s_rmap[d];
055     ++digs;
056 }
057
058 /* reverse the digits of the string. In this case _s points
059  * to the first digit [excluding the sign] of the number]
060  */
061 bn_reverse ((unsigned char *)_s, digs);
062
063 /* append a NULL so the string is properly terminated */
064 *str = '\0';
065
066 mp_clear (&t);
067 return MP_OKAY;
068 }
069
```

Chapter 9

Number Theoretic Algorithms

This chapter discusses several fundamental number theoretic algorithms such as the greatest common divisor, least common multiple and Jacobi symbol computation. These algorithms arise as essential components in several key cryptographic algorithms such as the RSA public key algorithm and various Sieve based factoring algorithms.

9.1 Greatest Common Divisor

The greatest common divisor of two integers a and b , often denoted as (a, b) is the largest integer k that is a proper divisor of both a and b . That is, k is the largest integer such that $0 \equiv a \pmod{k}$ and $0 \equiv b \pmod{k}$ occur simultaneously.

The most common approach (cite) is to reduce one input modulo another. That is if a and b are divisible by some integer k and if $qa + r = b$ then r is also divisible by k . The reduction pattern follows $\langle a, b \rangle \rightarrow \langle b, a \bmod b \rangle$.

Algorithm **Greatest Common Divisor (I)**.
Input. Two positive integers a and b greater than zero.
Output. The greatest common divisor (a, b) .

1. While $(b > 0)$ do
 - 1.1 $r \leftarrow a \pmod{b}$
 - 1.2 $a \leftarrow b$
 - 1.3 $b \leftarrow r$
2. Return(a).

Figure 9.1: Algorithm Greatest Common Divisor (I)

This algorithm will quickly converge on the greatest common divisor since the residue r tends to diminish rapidly. However, divisions are relatively expensive operations to perform and should ideally be avoided. There is another approach based on a similar relationship of greatest common divisors. The faster approach is based on the observation that if k divides both a and b it will also divide $a - b$. In particular, we would like $a - b$ to decrease in magnitude which implies that $b \geq a$.

Algorithm **Greatest Common Divisor (II)**.
Input. Two positive integers a and b greater than zero.
Output. The greatest common divisor (a, b) .

1. While $(b > 0)$ do
 - 1.1 Swap a and b such that a is the smallest of the two.
 - 1.2 $b \leftarrow b - a$
2. Return(a).

Figure 9.2: Algorithm Greatest Common Divisor (II)

Proof Algorithm 9.2 will return the greatest common divisor of a and b . The algorithm in figure 9.2 will eventually terminate since $b \geq a$ the subtraction in step 1.2 will be a value less than b . In other words in every iteration that tuple $\langle a, b \rangle$ decrease in magnitude until eventually $a = b$. Since both a and b are always divisible by the greatest common divisor (*until the last iteration*) and in the last iteration of the algorithm $b = 0$, therefore, in the second to last iteration of the algorithm $b = a$ and clearly $(a, a) = a$ which concludes the proof. **QED.**

As a matter of practicality algorithm 9.1 decreases far too slowly to be useful.

Specially if b is much larger than a such that $b - a$ is still very much larger than a . A simple addition to the algorithm is to divide $b - a$ by a power of some integer p which does not divide the greatest common divisor but will divide $b - a$. In this case $\frac{b-a}{p}$ is also an integer and still divisible by the greatest common divisor.

However, instead of factoring $b - a$ to find a suitable value of p the powers of p can be removed from a and b that are in common first. Then inside the loop whenever $b - a$ is divisible by some power of p it can be safely removed.

Algorithm **Greatest Common Divisor (III)**.

Input. Two positive integers a and b greater than zero.

Output. The greatest common divisor (a, b) .

1. $k \leftarrow 0$
 2. While a and b are both divisible by p do
 - 2.1 $a \leftarrow \lfloor a/p \rfloor$
 - 2.2 $b \leftarrow \lfloor b/p \rfloor$
 - 2.3 $k \leftarrow k + 1$
 3. While a is divisible by p do
 - 3.1 $a \leftarrow \lfloor a/p \rfloor$
 4. While b is divisible by p do
 - 4.1 $b \leftarrow \lfloor b/p \rfloor$
 5. While $(b > 0)$ do
 - 5.1 Swap a and b such that a is the smallest of the two.
 - 5.2 $b \leftarrow b - a$
 - 5.3 While b is divisible by p do
 - 5.3.1 $b \leftarrow \lfloor b/p \rfloor$
 6. Return($a \cdot p^k$).
-

Figure 9.3: Algorithm Greatest Common Divisor (III)

This algorithm is based on the first except it removes powers of p first and inside the main loop to ensure the tuple $\langle a, b \rangle$ decreases more rapidly. The first loop on step two removes powers of p that are in common. A count, k , is kept which will present a common divisor of p^k . After step two the remaining common divisor of a and b cannot be divisible by p . This means that p can be safely divided out of the difference $b - a$ so long as the division leaves no remainder.

In particular the value of p should be chosen such that the division on step 5.3.1 occur often. It also helps that division by p be easy to compute. The ideal

choice of p is two since division by two amounts to a right logical shift. Another important observation is that by step five both a and b are odd. Therefore, the difference $b - a$ must be even which means that each iteration removes one bit from the largest of the pair.

9.1.1 Complete Greatest Common Divisor

The algorithms presented so far cannot handle inputs which are zero or negative. The following algorithm can handle all input cases properly and will produce the greatest common divisor.

Algorithm **mp_gcd**.

Input. mp_int a and b

Output. The greatest common divisor $c = (a, b)$.

1. If $a = 0$ and $b \neq 0$ then
 - 1.1 $c \leftarrow b$
 - 1.2 Return(*MP_OKAY*).
 2. If $a \neq 0$ and $b = 0$ then
 - 2.1 $c \leftarrow a$
 - 2.2 Return(*MP_OKAY*).
 3. If $a = b = 0$ then
 - 3.1 $c \leftarrow 1$
 - 3.2 Return(*MP_OKAY*).
 4. $u \leftarrow |a|, v \leftarrow |b|$
 5. $k \leftarrow 0$
 6. While $u.used > 0$ and $v.used > 0$ and $u_0 \equiv v_0 \equiv 0 \pmod{2}$
 - 6.1 $k \leftarrow k + 1$
 - 6.2 $u \leftarrow \lfloor u/2 \rfloor$
 - 6.3 $v \leftarrow \lfloor v/2 \rfloor$
 7. While $u.used > 0$ and $u_0 \equiv 0 \pmod{2}$
 - 7.1 $u \leftarrow \lfloor u/2 \rfloor$
 8. While $v.used > 0$ and $v_0 \equiv 0 \pmod{2}$
 - 8.1 $v \leftarrow \lfloor v/2 \rfloor$
 9. While $v.used > 0$
 - 9.1 If $|u| > |v|$ then
 - 9.1.1 Swap u and v .
 - 9.2 $v \leftarrow |v| - |u|$
 - 9.3 While $v.used > 0$ and $v_0 \equiv 0 \pmod{2}$
 - 9.3.1 $v \leftarrow \lfloor v/2 \rfloor$
 10. $c \leftarrow u \cdot 2^k$
 11. Return(*MP_OKAY*).
-

Figure 9.4: Algorithm mp_gcd

Algorithm mp_gcd. This algorithm will produce the greatest common divisor of two mp_ints a and b . The algorithm was originally based on Algorithm B of Knuth [1, pp. 338] but has been modified to be simpler to explain. In theory it achieves the same asymptotic working time as Algorithm B and in practice this appears to be true.

The first three steps handle the cases where either one of or both inputs are zero. If either input is zero the greatest common divisor is the largest input or

zero if they are both zero. If the inputs are not trivial then u and v are assigned the absolute values of a and b respectively and the algorithm will proceed to reduce the pair.

Step six will divide out any common factors of two and keep track of the count in the variable k . After this step two is no longer a factor of the remaining greatest common divisor between u and v and can be safely evenly divided out of either whenever they are even. Step seven and eight ensure that the u and v respectively have no more factors of two. At most only one of the while loops will iterate since they cannot both be even.

By step nine both of u and v are odd which is required for the inner logic. First the pair are swapped such that v is equal to or greater than u . This ensures that the subtraction on step 9.2 will always produce a positive and even result. Step 9.3 removes any factors of two from the difference u to ensure that in the next iteration of the loop both are once again odd.

After $v = 0$ occurs the variable u has the greatest common divisor of the pair $\langle u, v \rangle$ just after step six. The result must be adjusted by multiplying by the common factors of two (2^k) removed earlier.

File: bn_mp_gcd.c

```

016
017  /* Greatest Common Divisor using the binary method */
018  int mp_gcd (mp_int * a, mp_int * b, mp_int * c)
019  {
020      mp_int  u, v;
021      int     k, u_lsb, v_lsb, res;
022
023      /* either zero than gcd is the largest */
024      if (mp_iszero (a) == 1 && mp_iszero (b) == 0) {
025          return mp_abs (b, c);
026      }
027      if (mp_iszero (a) == 0 && mp_iszero (b) == 1) {
028          return mp_abs (a, c);
029      }
030
031      /* optimized. At this point if a == 0 then
032       * b must equal zero too
033       */
034      if (mp_iszero (a) == 1) {
035          mp_zero(c);
036          return MP_OKAY;
037      }

```



```
038
039     /* get copies of a and b we can modify */
040     if ((res = mp_init_copy (&u, a)) != MP_OKAY) {
041         return res;
042     }
043
044     if ((res = mp_init_copy (&v, b)) != MP_OKAY) {
045         goto __U;
046     }
047
048     /* must be positive for the remainder of the algorithm */
049     u.sign = v.sign = MP_ZPOS;
050
051     /* B1. Find the common power of two for u and v */
052     u_lsb = mp_cnt_lsb(&u);
053     v_lsb = mp_cnt_lsb(&v);
054     k     = MIN(u_lsb, v_lsb);
055
056     if (k > 0) {
057         /* divide the power of two out */
058         if ((res = mp_div_2d(&u, k, &u, NULL)) != MP_OKAY) {
059             goto __V;
060         }
061
062         if ((res = mp_div_2d(&v, k, &v, NULL)) != MP_OKAY) {
063             goto __V;
064         }
065     }
066
067     /* divide any remaining factors of two out */
068     if (u_lsb != k) {
069         if ((res = mp_div_2d(&u, u_lsb - k, &u, NULL)) != MP_OKAY) {
070             goto __V;
071         }
072     }
073
074     if (v_lsb != k) {
075         if ((res = mp_div_2d(&v, v_lsb - k, &v, NULL)) != MP_OKAY) {
076             goto __V;
077         }
078     }
079
```

```

080 while (mp_iszero(&v) == 0) {
081     /* make sure v is the largest */
082     if (mp_cmp_mag(&u, &v) == MP_GT) {
083         /* swap u and v to make sure v is >= u */
084         mp_exch(&u, &v);
085     }
086
087     /* subtract smallest from largest */
088     if ((res = s_mp_sub(&v, &u, &v)) != MP_OKAY) {
089         goto __V;
090     }
091
092     /* Divide out all factors of two */
093     if ((res = mp_div_2d(&v, mp_cnt_lsb(&v), &v, NULL)) != MP_OKAY) {
094         goto __V;
095     }
096 }
097
098 /* multiply by 2**k which we divided out at the beginning */
099 if ((res = mp_mul_2d (&u, k, c)) != MP_OKAY) {
100     goto __V;
101 }
102 c->sign = MP_ZPOS;
103 res = MP_OKAY;
104 __V:mp_clear (&u);
105 __U:mp_clear (&v);
106 return res;
107 }

```

This function makes use of the macros `mp_iszero` and `mp_iseven`. The former evaluates to 1 if the input `mp_int` is equivalent to the integer zero otherwise it evaluates to 0. The latter evaluates to 1 if the input `mp_int` represents a non-zero even integer otherwise it evaluates to 0. Note that just because `mp_iseven` may evaluate to 0 does not mean the input is odd, it could also be zero. The three trivial cases of inputs are handled on lines 24 through 37. After those lines the inputs are assumed to be non-zero.

Lines 34 and 40 make local copies u and v of the inputs a and b respectively. At this point the common factors of two must be divided out of the two inputs. The while loop on line 80 iterates so long as both are even. The local integer k is used to keep track of how many factors of 2 are pulled out of both values. It is assumed that the number of factors will not exceed the maximum value of a

C “int” data type¹.

At this point there are no more common factors of two in the two values. The while loops on lines 80 and 80 remove any independent factors of two such that both u and v are guaranteed to be an odd integer before hitting the main body of the algorithm. The while loop on line 80 performs the reduction of the pair until v is equal to zero. The unsigned comparison and subtraction algorithms are used in place of the full signed routines since both values are guaranteed to be positive and the result of the subtraction is guaranteed to be non-negative.

9.2 Least Common Multiple

The least common multiple of a pair of integers is their product divided by their greatest common divisor. For two integers a and b the least common multiple is normally denoted as $[a, b]$ and numerically equivalent to $\frac{ab}{\gcd(a, b)}$. For example, if $a = 2 \cdot 2 \cdot 3 = 12$ and $b = 2 \cdot 3 \cdot 3 \cdot 7 = 126$ the least common multiple is $\frac{126}{\gcd(12, 126)} = \frac{126}{6} = 21$.

The least common multiple arises often in coding theory as well as number theory. If two functions have periods of a and b respectively they will collide, that is be in synchronous states, after only $[a, b]$ iterations. This is why, for example, random number generators based on Linear Feedback Shift Registers (LFSR) tend to use registers with periods which are co-prime (*e.g. the greatest common divisor is one.*). Similarly in number theory if a composite n has two prime factors p and q then maximal order of any unit of $\mathbb{Z}/n\mathbb{Z}$ will be $[p-1, q-1]$.

Algorithm **mp_lcm**.

Input. mp_int a and b

Output. The least common multiple $c = [a, b]$.

1. $c \leftarrow (a, b)$
 2. $t \leftarrow a \cdot b$
 3. $c \leftarrow \lfloor t/c \rfloor$
 4. Return(*MP_OKAY*).
-

Figure 9.5: Algorithm mp_lcm

Algorithm mp_lcm. This algorithm computes the least common multiple

¹Strictly speaking no array in C may have more than entries than are accessible by an “int” so this is not a limitation.

of two `mp_int` inputs a and b . It computes the least common multiple directly by dividing the product of the two inputs by their greatest common divisor.

File: `bn_mp_lcm.c`

```

016
017 /* computes least common multiple as |a*b|/(a, b) */
018 int mp_lcm (mp_int * a, mp_int * b, mp_int * c)
019 {
020     int     res;
021     mp_int  t1, t2;
022
023
024     if ((res = mp_init_multi (&t1, &t2, NULL)) != MP_OKAY) {
025         return res;
026     }
027
028     /* t1 = get the GCD of the two inputs */
029     if ((res = mp_gcd (a, b, &t1)) != MP_OKAY) {
030         goto __T;
031     }
032
033     /* divide the smallest by the GCD */
034     if (mp_cmp_mag(a, b) == MP_LT) {
035         /* store quotient in t2 such that t2 * b is the LCM */
036         if ((res = mp_div(a, &t1, &t2, NULL)) != MP_OKAY) {
037             goto __T;
038         }
039         res = mp_mul(b, &t2, c);
040     } else {
041         /* store quotient in t2 such that t2 * a is the LCM */
042         if ((res = mp_div(b, &t1, &t2, NULL)) != MP_OKAY) {
043             goto __T;
044         }
045         res = mp_mul(a, &t2, c);
046     }
047
048     /* fix the sign to positive */
049     c->sign = MP_ZPOS;
050
051 __T:
052     mp_clear_multi (&t1, &t2, NULL);
053     return res;
054 }
```

9.3 Jacobi Symbol Computation

To explain the Jacobi Symbol we shall first discuss the Legendre function² off which the Jacobi symbol is defined. The Legendre function computes whether or not an integer a is a quadratic residue modulo an odd prime p . Numerically it is equivalent to equation 9.1.

$$a^{(p-1)/2} \equiv \begin{cases} -1 & \text{if } a \text{ is a quadratic non-residue.} \\ 0 & \text{if } a \text{ divides } p. \\ 1 & \text{if } a \text{ is a quadratic residue.} \end{cases} \pmod{p} \quad (9.1)$$

Proof. Equation 9.1 correctly identifies the residue status of an integer a modulo a prime p . An integer a is a quadratic residue if the following equation has a solution.

$$x^2 \equiv a \pmod{p} \quad (9.2)$$

Consider the following equation.

$$0 \equiv x^{p-1} - 1 \equiv \left\{ (x^2)^{(p-1)/2} - a^{(p-1)/2} \right\} + \left(a^{(p-1)/2} - 1 \right) \pmod{p} \quad (9.3)$$

Whether equation 9.2 has a solution or not equation 9.3 is always true. If $a^{(p-1)/2} - 1 \equiv 0 \pmod{p}$ then the quantity in the braces must be zero. By reduction,

$$\begin{aligned} (x^2)^{(p-1)/2} - a^{(p-1)/2} &\equiv 0 \\ (x^2)^{(p-1)/2} &\equiv a^{(p-1)/2} \\ x^2 &\equiv a \pmod{p} \end{aligned} \quad (9.4)$$

As a result there must be a solution to the quadratic equation and in turn a must be a quadratic residue. If a does not divide p and a is not a quadratic residue then the only other value $a^{(p-1)/2}$ may be congruent to is -1 since

$$0 \equiv a^{p-1} - 1 \equiv (a^{(p-1)/2} + 1)(a^{(p-1)/2} - 1) \pmod{p} \quad (9.5)$$

One of the terms on the right hand side must be zero. **QED**

²Arrg. What is the name of this?

9.3.1 Jacobi Symbol

The Jacobi symbol is a generalization of the Legendre function for any odd non prime moduli p greater than 2. If $p = \prod_{i=0}^n p_i$ then the Jacobi symbol $\left(\frac{a}{p}\right)$ is equal to the following equation.

$$\left(\frac{a}{p}\right) = \left(\frac{a}{p_0}\right) \left(\frac{a}{p_1}\right) \cdots \left(\frac{a}{p_n}\right) \quad (9.6)$$

By inspection if p is prime the Jacobi symbol is equivalent to the Legendre function. The following facts³ will be used to derive an efficient Jacobi symbol algorithm. Where p is an odd integer greater than two and $a, b \in \mathbb{Z}$ the following are true.

1. $\left(\frac{a}{p}\right)$ equals $-1, 0$ or 1 .
2. $\left(\frac{ab}{p}\right) = \left(\frac{a}{p}\right) \left(\frac{b}{p}\right)$.
3. If $a \equiv b$ then $\left(\frac{a}{p}\right) = \left(\frac{b}{p}\right)$.
4. $\left(\frac{2}{p}\right)$ equals 1 if $p \equiv 1$ or $7 \pmod{8}$. Otherwise, it equals -1 .
5. $\left(\frac{a}{p}\right) \equiv \left(\frac{p}{a}\right) \cdot (-1)^{(p-1)(a-1)/4}$. More specifically $\left(\frac{a}{p}\right) = \left(\frac{p}{a}\right)$ if $p \equiv a \equiv 1 \pmod{4}$.

Using these facts if $a = 2^k \cdot a'$ then

$$\begin{aligned} \left(\frac{a}{p}\right) &= \left(\frac{2^k}{p}\right) \left(\frac{a'}{p}\right) \\ &= \left(\frac{2}{p}\right)^k \left(\frac{a'}{p}\right) \end{aligned} \quad (9.7)$$

By fact five,

$$\left(\frac{a}{p}\right) = \left(\frac{p}{a}\right) \cdot (-1)^{(p-1)(a-1)/4} \quad (9.8)$$

³See HAC [2, pp. 72-74] for further details.

Subsequently by fact three since $p \equiv (p \bmod a) \pmod{a}$ then

$$\left(\frac{a}{p}\right) = \left(\frac{p \bmod a}{a}\right) \cdot (-1)^{(p-1)(a-1)/4} \quad (9.9)$$

By putting both observations into equation 9.7 the following simplified equation is formed.

$$\left(\frac{a}{p}\right) = \left(\frac{2}{p}\right)^k \left(\frac{p \bmod a'}{a'}\right) \cdot (-1)^{(p-1)(a'-1)/4} \quad (9.10)$$

The value of $\left(\frac{p \bmod a'}{a'}\right)$ can be found by using the same equation recursively. The value of $\left(\frac{2}{p}\right)^k$ equals 1 if k is even otherwise it equals $\left(\frac{2}{p}\right)$. Using this approach the factors of p do not have to be known. Furthermore, if $(a, p) = 1$ then the algorithm will terminate when the recursion requests the Jacobi symbol computation of $\left(\frac{1}{a'}\right)$ which is simply 1.

Algorithm mp_jacobi.
Input. mp_int a and p , $a \geq 0$, $p \geq 3$, $p \equiv 1 \pmod{2}$
Output. The Jacobi symbol $c = \left(\frac{a}{p}\right)$.

1. If $a = 0$ then
 - 1.1 $c \leftarrow 0$
 - 1.2 Return(*MP_OKAY*).
2. If $a = 1$ then
 - 2.1 $c \leftarrow 1$
 - 2.2 Return(*MP_OKAY*).
3. $a' \leftarrow a$
4. $k \leftarrow 0$
5. While $a'.used > 0$ and $a'_0 \equiv 0 \pmod{2}$
 - 5.1 $k \leftarrow k + 1$
 - 5.2 $a' \leftarrow \lfloor a'/2 \rfloor$
6. If $k \equiv 0 \pmod{2}$ then
 - 6.1 $s \leftarrow 1$
7. else
 - 7.1 $r \leftarrow p_0 \pmod{8}$
 - 7.2 If $r = 1$ or $r = 7$ then
 - 7.2.1 $s \leftarrow 1$
 - 7.3 else
 - 7.3.1 $s \leftarrow -1$
8. If $p_0 \equiv a'_0 \equiv 3 \pmod{4}$ then
 - 8.1 $s \leftarrow -s$
9. If $a' \neq 1$ then
 - 9.1 $p' \leftarrow p \pmod{a'}$
 - 9.2 $s \leftarrow s \cdot \text{mp_jacobi}(p', a')$
10. $c \leftarrow s$
11. Return(*MP_OKAY*).

Figure 9.6: Algorithm mp_jacobi

Algorithm mp_jacobi. This algorithm computes the Jacobi symbol for an arbitrary positive integer a with respect to an odd integer p greater than three. The algorithm is based on algorithm 2.149 of HAC [2, pp. 73].

Step numbers one and two handle the trivial cases of $a = 0$ and $a = 1$ respectively. Step five determines the number of two factors in the input a . If k is even then the term $\left(\frac{2}{p}\right)^k$ must always evaluate to one. If k is odd then the term evaluates to one if p_0 is congruent to one or seven modulo eight, otherwise

it evaluates to -1 . After the the $\left(\frac{2}{p}\right)^k$ term is handled the $(-1)^{(p-1)(a'-1)/4}$ is computed and multiplied against the current product s . The latter term evaluates to one if both p and a' are congruent to one modulo four, otherwise it evaluates to negative one.

By step nine if a' does not equal one a recursion is required. Step 9.1 computes $p' \equiv p \pmod{a'}$ and will recurse to compute $\left(\frac{p'}{a'}\right)$ which is multiplied against the current Jacobi product.

File: bn_mp_jacobi.c

```

016
017  /* computes the jacobi c = (a | n) (or Legendre if n is prime)
018   * HAC pp. 73 Algorithm 2.149
019   */
020  int mp_jacobi (mp_int * a, mp_int * p, int *c)
021  {
022      mp_int  a1, p1;
023      int     k, s, r, res;
024      mp_digit residue;
025
026      /* if p <= 0 return MP_VAL */
027      if (mp_cmp_d(p, 0) != MP_GT) {
028          return MP_VAL;
029      }
030
031      /* step 1.  if a == 0, return 0 */
032      if (mp_iszero (a) == 1) {
033          *c = 0;
034          return MP_OKAY;
035      }
036
037      /* step 2.  if a == 1, return 1 */
038      if (mp_cmp_d (a, 1) == MP_EQ) {
039          *c = 1;
040          return MP_OKAY;
041      }
042
043      /* default */
044      s = 0;
045
046      /* step 3.  write a = a1 * 2**k */
047      if ((res = mp_init_copy (&a1, a)) != MP_OKAY) {

```

```

048     return res;
049 }
050
051 if ((res = mp_init (&p1)) != MP_OKAY) {
052     goto __A1;
053 }
054
055 /* divide out larger power of two */
056 k = mp_cnt_lsb(&a1);
057 if ((res = mp_div_2d(&a1, k, &a1, NULL)) != MP_OKAY) {
058     goto __P1;
059 }
060
061 /* step 4.  if e is even set s=1 */
062 if ((k & 1) == 0) {
063     s = 1;
064 } else {
065     /* else set s=1 if p = 1/7 (mod 8) or s=-1 if p = 3/5 (mod 8) */
066     residue = p->dp[0] & 7;
067
068     if (residue == 1 || residue == 7) {
069         s = 1;
070     } else if (residue == 3 || residue == 5) {
071         s = -1;
072     }
073 }
074
075 /* step 5.  if p == 3 (mod 4) *and* a1 == 3 (mod 4) then s = -s */
076 if ((p->dp[0] & 3) == 3 && ((a1.dp[0] & 3) == 3)) {
077     s = -s;
078 }
079
080 /* if a1 == 1 we're done */
081 if (mp_cmp_d (&a1, 1) == MP_EQ) {
082     *c = s;
083 } else {
084     /* n1 = n mod a1 */
085     if ((res = mp_mod (p, &a1, &p1)) != MP_OKAY) {
086         goto __P1;
087     }
088     if ((res = mp_jacobi (&p1, &a1, &r)) != MP_OKAY) {
089         goto __P1;

```

```

090     }
091     *c = s * r;
092     }
093
094     /* done */
095     res = MP_OKAY;
096     __P1:mp_clear (&p1);
097     __A1:mp_clear (&a1);
098     return res;
099 }

```

As a matter of practicality the variable a' as per the pseudo-code is represented by the variable $a1$ since the $'$ symbol is not valid for a C variable name character.

The two simple cases of $a = 0$ and $a = 1$ are handled at the very beginning to simplify the algorithm. If the input is non-trivial the algorithm has to proceed compute the Jacobi. The variable s is used to hold the current Jacobi product. Note that s is merely a C “int” data type since the values it may obtain are merely -1 , 0 and 1 .

After a local copy of a is made all of the factors of two are divided out and the total stored in k . Technically only the least significant bit of k is required, however, it makes the algorithm simpler to follow to perform an addition. In practice an exclusive-or and addition have the same processor requirements and neither is faster than the other.

Line 61 through 70 determines the value of $\left(\frac{2}{p}\right)^k$. If the least significant bit of k is zero then k is even and the value is one. Otherwise, the value of s depends on which residue class p belongs to modulo eight. The value of $(-1)^{(p-1)(a'-1)/4}$ is compute and multiplied against s on lines 75 through 73.

Finally, if $a1$ does not equal one the algorithm must recurse and compute $\left(\frac{p'}{a'}\right)$.

– *Comment about default s and such...*

9.4 Modular Inverse

The modular inverse of a number actually refers to the modular multiplicative inverse. Essentially for any integer a such that $(a, p) = 1$ there exist another integer b such that $ab \equiv 1 \pmod{p}$. The integer b is called the multiplicative inverse of a which is denoted as $b = a^{-1}$. Technically speaking modular inversion is a well defined operation for any finite ring or field not just for rings and fields of integers. However, the former will be the matter of discussion.

The simplest approach is to compute the algebraic inverse of the input. That is to compute $b \equiv a^{\Phi(p)-1}$. If $\Phi(p)$ is the order of the multiplicative subgroup modulo p then b must be the multiplicative inverse of a . The proof of which is trivial.

$$ab \equiv a \left(a^{\Phi(p)-1} \right) \equiv a^{\Phi(p)} \equiv a^0 \equiv 1 \pmod{p} \quad (9.11)$$

However, as simple as this approach may be it has two serious flaws. It requires that the value of $\Phi(p)$ be known which if p is composite requires all of the prime factors. This approach also is very slow as the size of p grows.

A simpler approach is based on the observation that solving for the multiplicative inverse is equivalent to solving the linear Diophantine⁴ equation.

$$ab + pq = 1 \quad (9.12)$$

Where a , b , p and q are all integers. If such a pair of integers $\langle b, q \rangle$ exist than b is the multiplicative inverse of a modulo p . The extended Euclidean algorithm (Knuth [1, pp. 342]) can be used to solve such equations provided $(a, p) = 1$. However, instead of using that algorithm directly a variant known as the binary Extended Euclidean algorithm will be used in its place. The binary approach is very similar to the binary greatest common divisor algorithm except it will produce a full solution to the Diophantine equation.

9.4.1 General Case

⁴See LeVeque [?, pp. 40-43] for more information.

Algorithm **mp_invmod**.

Input. mp_int a and b , $(a, b) = 1$, $p \geq 2$, $0 < a < p$.

Output. The modular inverse $c \equiv a^{-1} \pmod{b}$.

1. If $b \leq 0$ then return(*MP_VAL*).
 2. If $b_0 \equiv 1 \pmod{2}$ then use algorithm *fast_mp_invmod*.
 3. $x \leftarrow |a|, y \leftarrow b$
 4. If $x_0 \equiv y_0 \equiv 0 \pmod{2}$ then return(*MP_VAL*).
 5. $B \leftarrow 0, C \leftarrow 0, A \leftarrow 1, D \leftarrow 1$
 6. While $u.used > 0$ and $u_0 \equiv 0 \pmod{2}$
 - 6.1 $u \leftarrow \lfloor u/2 \rfloor$
 - 6.2 If $(A.used > 0$ and $A_0 \equiv 1 \pmod{2})$ or $(B.used > 0$ and $B_0 \equiv 1 \pmod{2})$ then
 - 6.2.1 $A \leftarrow A + y$
 - 6.2.2 $B \leftarrow B - x$
 - 6.3 $A \leftarrow \lfloor A/2 \rfloor$
 - 6.4 $B \leftarrow \lfloor B/2 \rfloor$
 7. While $v.used > 0$ and $v_0 \equiv 0 \pmod{2}$
 - 7.1 $v \leftarrow \lfloor v/2 \rfloor$
 - 7.2 If $(C.used > 0$ and $C_0 \equiv 1 \pmod{2})$ or $(D.used > 0$ and $D_0 \equiv 1 \pmod{2})$ then
 - 7.2.1 $C \leftarrow C + y$
 - 7.2.2 $D \leftarrow D - x$
 - 7.3 $C \leftarrow \lfloor C/2 \rfloor$
 - 7.4 $D \leftarrow \lfloor D/2 \rfloor$
 8. If $u \geq v$ then
 - 8.1 $u \leftarrow u - v$
 - 8.2 $A \leftarrow A - C$
 - 8.3 $B \leftarrow B - D$
 9. else
 - 9.1 $v \leftarrow v - u$
 - 9.2 $C \leftarrow C - A$
 - 9.3 $D \leftarrow D - B$
 10. If $u \neq 0$ goto step 6.
 11. If $v \neq 1$ return(*MP_VAL*).
 12. While $C \leq 0$ do
 - 12.1 $C \leftarrow C + b$
 13. While $C \geq b$ do
 - 13.1 $C \leftarrow C - b$
 14. $c \leftarrow C$
 15. Return(*MP_OKAY*).
-

Algorithm mp_invmod. This algorithm computes the modular multi-

plicative inverse of an integer a modulo an integer b . This algorithm is a variation of the extended binary Euclidean algorithm from HAC [2, pp. 608]. It has been modified to only compute the modular inverse and not a complete Diophantine solution.

If $b \leq 0$ then the modulus is invalid and MP_VAL is returned. Similarly if both a and b are even then there cannot be a multiplicative inverse for a and the error is reported.

The astute reader will observe that steps seven through nine are very similar to the binary greatest common divisor algorithm mp_gcd. In this case the other variables to the Diophantine equation are solved. The algorithm terminates when $u = 0$ in which case the solution is

$$Ca + Db = v \tag{9.13}$$

If v , the greatest common divisor of a and b is not equal to one then the algorithm will report an error as no inverse exists. Otherwise, C is the modular inverse of a . The actual value of C is congruent to, but not necessarily equal to, the ideal modular inverse which should lie within $1 \leq a^{-1} < b$. Step numbers twelve and thirteen adjust the inverse until it is in range. If the original input a is within $0 < a < p$ then only a couple of additions or subtractions will be required to adjust the inverse.

File: bn_mp_invmod.c

```

016
017  /* hac 14.61, pp608 */
018  int mp_invmod (mp_int * a, mp_int * b, mp_int * c)
019  {
020      mp_int  x, y, u, v, A, B, C, D;
021      int     res;
022
023      /* b cannot be negative */
024      if (b->sign == MP_NEG || mp_iszero(b) == 1) {
025          return MP_VAL;
026      }
027
028      /* if the modulus is odd we can use a faster routine instead */
029      if (mp_isodd (b) == 1) {
030          return fast_mp_invmod (a, b, c);
031      }
032
033      /* init temps */

```

```

034     if ((res = mp_init_multi(&x, &y, &u, &v,
035                             &A, &B, &C, &D, NULL)) != MP_OKAY) {
036         return res;
037     }
038
039     /* x = a, y = b */
040     if ((res = mp_copy (a, &x)) != MP_OKAY) {
041         goto __ERR;
042     }
043     if ((res = mp_copy (b, &y)) != MP_OKAY) {
044         goto __ERR;
045     }
046
047     /* 2. [modified] if x,y are both even then return an error! */
048     if (mp_iseven (&x) == 1 && mp_iseven (&y) == 1) {
049         res = MP_VAL;
050         goto __ERR;
051     }
052
053     /* 3. u=x, v=y, A=1, B=0, C=0,D=1 */
054     if ((res = mp_copy (&x, &u)) != MP_OKAY) {
055         goto __ERR;
056     }
057     if ((res = mp_copy (&y, &v)) != MP_OKAY) {
058         goto __ERR;
059     }
060     mp_set (&A, 1);
061     mp_set (&D, 1);
062
063     top:
064     /* 4. while u is even do */
065     while (mp_iseven (&u) == 1) {
066         /* 4.1 u = u/2 */
067         if ((res = mp_div_2 (&u, &u)) != MP_OKAY) {
068             goto __ERR;
069         }
070         /* 4.2 if A or B is odd then */
071         if (mp_isodd (&A) == 1 || mp_isodd (&B) == 1) {
072             /* A = (A+y)/2, B = (B-x)/2 */
073             if ((res = mp_add (&A, &y, &A)) != MP_OKAY) {
074                 goto __ERR;
075             }

```

```

076     if ((res = mp_sub (&B, &x, &B)) != MP_OKAY) {
077         goto __ERR;
078     }
079 }
080 /* A = A/2, B = B/2 */
081 if ((res = mp_div_2 (&A, &A)) != MP_OKAY) {
082     goto __ERR;
083 }
084 if ((res = mp_div_2 (&B, &B)) != MP_OKAY) {
085     goto __ERR;
086 }
087 }
088
089 /* 5. while v is even do */
090 while (mp_iseven (&v) == 1) {
091     /* 5.1 v = v/2 */
092     if ((res = mp_div_2 (&v, &v)) != MP_OKAY) {
093         goto __ERR;
094     }
095     /* 5.2 if C or D is odd then */
096     if (mp_isodd (&C) == 1 || mp_isodd (&D) == 1) {
097         /* C = (C+y)/2, D = (D-x)/2 */
098         if ((res = mp_add (&C, &y, &C)) != MP_OKAY) {
099             goto __ERR;
100         }
101         if ((res = mp_sub (&D, &x, &D)) != MP_OKAY) {
102             goto __ERR;
103         }
104     }
105     /* C = C/2, D = D/2 */
106     if ((res = mp_div_2 (&C, &C)) != MP_OKAY) {
107         goto __ERR;
108     }
109     if ((res = mp_div_2 (&D, &D)) != MP_OKAY) {
110         goto __ERR;
111     }
112 }
113
114 /* 6. if u >= v then */
115 if (mp_cmp (&u, &v) != MP_LT) {
116     /* u = u - v, A = A - C, B = B - D */
117     if ((res = mp_sub (&u, &v, &u)) != MP_OKAY) {

```



```
118     goto __ERR;
119 }
120
121     if ((res = mp_sub (&A, &C, &A)) != MP_OKAY) {
122         goto __ERR;
123     }
124
125     if ((res = mp_sub (&B, &D, &B)) != MP_OKAY) {
126         goto __ERR;
127     }
128 } else {
129     /* v - v - u, C = C - A, D = D - B */
130     if ((res = mp_sub (&v, &u, &v)) != MP_OKAY) {
131         goto __ERR;
132     }
133
134     if ((res = mp_sub (&C, &A, &C)) != MP_OKAY) {
135         goto __ERR;
136     }
137
138     if ((res = mp_sub (&D, &B, &D)) != MP_OKAY) {
139         goto __ERR;
140     }
141 }
142
143 /* if not zero goto step 4 */
144 if (mp_iszero (&u) == 0)
145     goto top;
146
147 /* now a = C, b = D, gcd == g*v */
148
149 /* if v != 1 then there is no inverse */
150 if (mp_cmp_d (&v, 1) != MP_EQ) {
151     res = MP_VAL;
152     goto __ERR;
153 }
154
155 /* if its too low */
156 while (mp_cmp_d (&C, 0) == MP_LT) {
157     if ((res = mp_add (&C, b, &C)) != MP_OKAY) {
158         goto __ERR;
159     }
```

```

160     }
161
162     /* too big */
163     while (mp_cmp_mag(&C, b) != MP_LT) {
164         if ((res = mp_sub(&C, b, &C)) != MP_OKAY) {
165             goto __ERR;
166         }
167     }
168
169     /* C is now the inverse */
170     mp_exch (&C, c);
171     res = MP_OKAY;
172     __ERR:mp_clear_multi (&x, &y, &u, &v, &A, &B, &C, &D, NULL);
173     return res;
174 }

```

Odd Moduli

When the modulus b is odd the variables A and C are fixed and are not required to compute the inverse. In particular by attempting to solve the Diophantine $Cb + Da = 1$ only B and D are required to find the inverse of a .

The algorithm `fast_mp_invmod` is a direct adaptation of algorithm `mp_invmod` with all steps involving either A or C removed. This optimization will halve the time required to compute the modular inverse.

9.5 Primality Tests

A non-zero integer a is said to be prime if it is not divisible by any other integer excluding one and itself. For example, $a = 7$ is prime since the integers $2 \dots 6$ do not evenly divide a . By contrast, $a = 6$ is not prime since $a = 6 = 2 \cdot 3$.

Prime numbers arise in cryptography considerably as they allow finite fields to be formed. The ability to determine whether an integer is prime or not quickly has been a viable subject in cryptography and number theory for considerable time. The algorithms that will be presented are all probabilistic algorithms in that when they report an integer is composite it must be composite. However, when the algorithms report an integer is prime the algorithm may be incorrect.

As will be discussed it is possible to limit the probability of error so well that for practical purposes the probability of error might as well be zero. For the purposes of these discussions let n represent the candidate integer of which the primality is in question.

9.5.1 Trial Division

Trial division means to attempt to evenly divide a candidate integer by small prime integers. If the candidate can be evenly divided it obviously cannot be prime. By dividing by all primes $1 < p \leq \sqrt{n}$ this test can actually prove whether an integer is prime. However, such a test would require a prohibitive amount of time as n grows.

Instead of dividing by every prime, a smaller, more manageable set of primes may be used instead. By performing trial division with only a subset of the primes less than $\sqrt{n} + 1$ the algorithm cannot prove if a candidate is prime. However, often it can prove a candidate is not prime.

The benefit of this test is that trial division by small values is fairly efficient. Specially compared to the other algorithms that will be discussed shortly. The probability that this approach correctly identifies a composite candidate when tested with all primes upto q is given by $1 - \frac{1.12}{\ln(q)}$. The graph (??, will be added later) demonstrates the probability of success for the range $3 \leq q \leq 100$.

At approximately $q = 30$ the gain of performing further tests diminishes fairly quickly. At $q = 90$ further testing is generally not going to be of any practical use. In the case of LibTomMath the default limit $q = 256$ was chosen since it is not too high and will eliminate approximately 80% of all candidate integers. The constant **PRIME_SIZE** is equal to the number of primes in the test base. The array `_prime.tab` is an array of the first **PRIME_SIZE** prime numbers.

Algorithm **mp_prime_is_divisible**.
Input. `mp_int a`
Output. $c = 1$ if n is divisible by a small prime, otherwise $c = 0$.

1. for ix from 0 to `PRIME_SIZE` do
 - 1.1 $d \leftarrow n \pmod{_prime.tab_{ix}}$
 - 1.2 If $d = 0$ then
 - 1.2.1 $c \leftarrow 1$
 - 1.2.2 Return(`MP_OKAY`).
2. $c \leftarrow 0$
3. Return(`MP_OKAY`).

Figure 9.7: Algorithm `mp_prime_is_divisible`

Algorithm `mp_prime_is_divisible`. This algorithm attempts to deter-

mine if a candidate integer n is composite by performing trial divisions.

File: bn_mp_prime_is_divisible.c

```

016
017 /* determines if an integers is divisible by one
018 * of the first PRIME_SIZE primes or not
019 *
020 * sets result to 0 if not, 1 if yes
021 */
022 int mp_prime_is_divisible (mp_int * a, int *result)
023 {
024     int     err, ix;
025     mp_digit res;
026
027     /* default to not */
028     *result = MP_NO;
029
030     for (ix = 0; ix < PRIME_SIZE; ix++) {
031         /* what is a mod __prime_tab[ix] */
032         if ((err = mp_mod_d (a, __prime_tab[ix], &res)) != MP_OKAY) {
033             return err;
034         }
035
036         /* is the residue zero? */
037         if (res == 0) {
038             *result = MP_YES;
039             return MP_OKAY;
040         }
041     }
042
043     return MP_OKAY;
044 }

```

The algorithm defaults to a return of 0 in case an error occurs. The values in the prime table are all specified to be in the range of a mp_digit. The table `__prime.tab` is defined in the following file.

File: bn_prime.tab.c

```

016 const mp_digit __prime_tab[] = {
017     0x0002, 0x0003, 0x0005, 0x0007, 0x000B, 0x000D, 0x0011, 0x0013,
018     0x0017, 0x001D, 0x001F, 0x0025, 0x0029, 0x002B, 0x002F, 0x0035,
019     0x003B, 0x003D, 0x0043, 0x0047, 0x0049, 0x004F, 0x0053, 0x0059,
020     0x0061, 0x0065, 0x0067, 0x006B, 0x006D, 0x0071, 0x007F,

```

```

021  #ifndef MP_8BIT
022      0x0083,
023      0x0089, 0x008B, 0x0095, 0x0097, 0x009D, 0x00A3, 0x00A7, 0x00AD,
024      0x00B3, 0x00B5, 0x00BF, 0x00C1, 0x00C5, 0x00C7, 0x00D3, 0x00DF,
025      0x00E3, 0x00E5, 0x00E9, 0x00EF, 0x00F1, 0x00FB, 0x0101, 0x0107,
026      0x010D, 0x010F, 0x0115, 0x0119, 0x011B, 0x0125, 0x0133, 0x0137,
027
028      0x0139, 0x013D, 0x014B, 0x0151, 0x015B, 0x015D, 0x0161, 0x0167,
029      0x016F, 0x0175, 0x017B, 0x017F, 0x0185, 0x018D, 0x0191, 0x0199,
030      0x01A3, 0x01A5, 0x01AF, 0x01B1, 0x01B7, 0x01BB, 0x01C1, 0x01C9,
031      0x01CD, 0x01CF, 0x01D3, 0x01DF, 0x01E7, 0x01EB, 0x01F3, 0x01F7,
032      0x01FD, 0x0209, 0x020B, 0x021D, 0x0223, 0x022D, 0x0233, 0x0239,
033      0x023B, 0x0241, 0x024B, 0x0251, 0x0257, 0x0259, 0x025F, 0x0265,
034      0x0269, 0x026B, 0x0277, 0x0281, 0x0283, 0x0287, 0x028D, 0x0293,
035      0x0295, 0x02A1, 0x02A5, 0x02AB, 0x02B3, 0x02BD, 0x02C5, 0x02CF,
036
037      0x02D7, 0x02DD, 0x02E3, 0x02E7, 0x02EF, 0x02F5, 0x02F9, 0x0301,
038      0x0305, 0x0313, 0x031D, 0x0329, 0x032B, 0x0335, 0x0337, 0x033B,
039      0x033D, 0x0347, 0x0355, 0x0359, 0x035B, 0x035F, 0x036D, 0x0371,
040      0x0373, 0x0377, 0x038B, 0x038F, 0x0397, 0x03A1, 0x03A9, 0x03AD,
041      0x03B3, 0x03B9, 0x03C7, 0x03CB, 0x03D1, 0x03D7, 0x03DF, 0x03E5,
042      0x03F1, 0x03F5, 0x03FB, 0x03FD, 0x0407, 0x0409, 0x040F, 0x0419,
043      0x041B, 0x0425, 0x0427, 0x042D, 0x043F, 0x0443, 0x0445, 0x0449,
044      0x044F, 0x0455, 0x045D, 0x0463, 0x0469, 0x047F, 0x0481, 0x048B,
045
046      0x0493, 0x049D, 0x04A3, 0x04A9, 0x04B1, 0x04BD, 0x04C1, 0x04C7,
047      0x04CD, 0x04CF, 0x04D5, 0x04E1, 0x04EB, 0x04FD, 0x04FF, 0x0503,
048      0x0509, 0x050B, 0x0511, 0x0515, 0x0517, 0x051B, 0x0527, 0x0529,
049      0x052F, 0x0551, 0x0557, 0x055D, 0x0565, 0x0577, 0x0581, 0x058F,
050      0x0593, 0x0595, 0x0599, 0x059F, 0x05A7, 0x05AB, 0x05AD, 0x05B3,
051      0x05BF, 0x05C9, 0x05CB, 0x05CF, 0x05D1, 0x05D5, 0x05DB, 0x05E7,
052      0x05F3, 0x05FB, 0x0607, 0x060D, 0x0611, 0x0617, 0x061F, 0x0623,
053      0x062B, 0x062F, 0x063D, 0x0641, 0x0647, 0x0649, 0x064D, 0x0653
054  #endif
055  };

```

Note that there are two possible tables. When an `mp_digit` is 7-bits long only the primes upto 127 may be included, otherwise the primes upto 1619 are used. Note that the value of `PRIME_SIZE` is a constant dependent on the size of a `mp_digit`.

9.5.2 The Fermat Test

The Fermat test is probably one the oldest tests to have a non-trivial probability of success. It is based on the fact that if n is in fact prime then $a^n \equiv a \pmod{n}$ for all $0 < a < n$. The reason being that if n is prime then the order of the multiplicative sub group is $n - 1$. Any base a must have an order which divides $n - 1$ and as such a^n is equivalent to $a^1 = a$.

If n is composite then any given base a does not have to have a period which divides $n - 1$. In which case it is possible that $a^n \not\equiv a \pmod{n}$. However, this test is not absolute as it is possible that the order of a base will divide $n - 1$ which would then be reported as prime. Such a base yields what is known as a Fermat pseudo-prime. Several integers known as Carmichael numbers will be a pseudo-prime to all valid bases. Fortunately such numbers are extremely rare as n grows in size.

Algorithm **mp_prime_fermat**.
Input. mp_int a and b , $a \geq 2$, $0 < b < a$.
Output. $c = 1$ if $b^a \equiv b \pmod{a}$, otherwise $c = 0$.

1. $t \leftarrow b^a \pmod{a}$
2. If $t = b$ then
 - 2.1 $c = 1$
3. else
 - 3.1 $c = 0$
4. Return(*MP_OKAY*).

Figure 9.8: Algorithm mp_prime_fermat

Algorithm mp_prime_fermat. This algorithm determines whether an mp_int a is a Fermat prime to the base b or not. It uses a single modular exponentiation to determine the result.

```
File: bn_mp_prime_fermat.c
016
017 /* performs one Fermat test.
018  *
019  * If "a" were prime then b**a == b (mod a) since the order of
020  * the multiplicative sub-group would be phi(a) = a-1. That means
021  * it would be the same as b**(a mod (a-1)) == b**1 == b (mod a).
022  *
023  * Sets result to 1 if the congruence holds, or zero otherwise.
```

```

024  */
025  int mp_prime_fermat (mp_int * a, mp_int * b, int *result)
026  {
027      mp_int t;
028      int err;
029
030      /* default to composite */
031      *result = MP_NO;
032
033      /* ensure b > 1 */
034      if (mp_cmp_d(b, 1) != MP_GT) {
035          return MP_VAL;
036      }
037
038      /* init t */
039      if ((err = mp_init (&t)) != MP_OKAY) {
040          return err;
041      }
042
043      /* compute t = b**a mod a */
044      if ((err = mp_exptmod (b, a, a, &t)) != MP_OKAY) {
045          goto __T;
046      }
047
048      /* is it equal to b? */
049      if (mp_cmp (&t, b) == MP_EQ) {
050          *result = MP_YES;
051      }
052
053      err = MP_OKAY;
054      __T:mp_clear (&t);
055      return err;
056  }

```

9.5.3 The Miller-Rabin Test

The Miller-Rabin (citation) test is another primality test which has tighter error bounds than the Fermat test specifically with sequentially chosen candidate integers. The algorithm is based on the observation that if $n - 1 = 2^k r$ and if $b^r \not\equiv \pm 1$ then after upto $k - 1$ squarings the value must be equal to -1 . The squarings are stopped as soon as -1 is observed. If the value of 1 is observed

first it means that some value not congruent to ± 1 when squared equals one which cannot occur if n is prime.

Algorithm **mp_prime_miller_rabin**.

Input. mp_int a and b , $a \geq 2$, $0 < b < a$.

Output. $c = 1$ if a is a Miller-Rabin prime to the base a , otherwise $c = 0$.

1. $a' \leftarrow a - 1$
 2. $r \leftarrow n1$
 3. $c \leftarrow 0, s \leftarrow 0$
 4. While $r.used > 0$ and $r_0 \equiv 0 \pmod{2}$
 - 4.1 $s \leftarrow s + 1$
 - 4.2 $r \leftarrow \lfloor r/2 \rfloor$
 5. $y \leftarrow b^r \pmod{a}$
 6. If $y \not\equiv \pm 1$ then
 - 6.1 $j \leftarrow 1$
 - 6.2 While $j \leq (s - 1)$ and $y \not\equiv a'$
 - 6.2.1 $y \leftarrow y^2 \pmod{a}$
 - 6.2.2 If $y = 1$ then goto step 8.
 - 6.2.3 $j \leftarrow j + 1$
 - 6.3 If $y \not\equiv a'$ goto step 8.
 7. $c \leftarrow 1$
 8. Return(*MP_OKAY*).
-

Figure 9.9: Algorithm mp_prime_miller_rabin

Algorithm mp_prime_miller_rabin. This algorithm performs one trial round of the Miller-Rabin algorithm to the base b . It will set $c = 1$ if the algorithm cannot determine if b is composite or $c = 0$ if b is provably composite. The values of s and r are computed such that $a' = a - 1 = 2^s r$.

If the value $y \equiv b^r$ is congruent to ± 1 then the algorithm cannot prove if a is composite or not. Otherwise, the algorithm will square y upto $s - 1$ times stopping only when $y \equiv -1$. If $y^2 \equiv 1$ and $y \not\equiv \pm 1$ then the algorithm can report that a is provably composite. If the algorithm performs $s - 1$ squarings and $y \not\equiv -1$ then a is provably composite. If a is not provably composite then it is *probably* prime.

File: bn_mp_prime_miller_rabin.c

```
016
017 /* Miller-Rabin test of "a" to the base of "b" as described in
018 * HAC pp. 139 Algorithm 4.24
019 *
```



```
020  * Sets result to 0 if definitely composite or 1 if probably prime.
021  * Randomly the chance of error is no more than 1/4 and often
022  * very much lower.
023  */
024  int mp_prime_miller_rabin (mp_int * a, mp_int * b, int *result)
025  {
026      mp_int  n1, y, r;
027      int     s, j, err;
028
029      /* default */
030      *result = MP_NO;
031
032      /* ensure b > 1 */
033      if (mp_cmp_d(b, 1) != MP_GT) {
034          return MP_VAL;
035      }
036
037      /* get n1 = a - 1 */
038      if ((err = mp_init_copy (&n1, a)) != MP_OKAY) {
039          return err;
040      }
041      if ((err = mp_sub_d (&n1, 1, &n1)) != MP_OKAY) {
042          goto __N1;
043      }
044
045      /* set 2**s * r = n1 */
046      if ((err = mp_init_copy (&r, &n1)) != MP_OKAY) {
047          goto __N1;
048      }
049
050      /* count the number of least significant bits
051       * which are zero
052       */
053      s = mp_cnt_lsb(&r);
054
055      /* now divide n - 1 by 2**s */
056      if ((err = mp_div_2d (&r, s, &r, NULL)) != MP_OKAY) {
057          goto __R;
058      }
059
060      /* compute y = b**r mod a */
061      if ((err = mp_init (&y)) != MP_OKAY) {
```

```
062     goto __R;
063 }
064 if ((err = mp_exptmod (b, &r, a, &y)) != MP_OKAY) {
065     goto __Y;
066 }
067
068 /* if y != 1 and y != n1 do */
069 if (mp_cmp_d (&y, 1) != MP_EQ && mp_cmp (&y, &n1) != MP_EQ) {
070     j = 1;
071     /* while j <= s-1 and y != n1 */
072     while ((j <= (s - 1)) && mp_cmp (&y, &n1) != MP_EQ) {
073         if ((err = mp_sqrmod (&y, a, &y)) != MP_OKAY) {
074             goto __Y;
075         }
076
077         /* if y == 1 then composite */
078         if (mp_cmp_d (&y, 1) == MP_EQ) {
079             goto __Y;
080         }
081
082         ++j;
083     }
084
085     /* if y != n1 then composite */
086     if (mp_cmp (&y, &n1) != MP_EQ) {
087         goto __Y;
088     }
089 }
090
091 /* probably prime now */
092 *result = MP_YES;
093 __Y:mp_clear (&y);
094 __R:mp_clear (&r);
095 __N1:mp_clear (&n1);
096 return err;
097 }
```

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