MACM 401/MATH 701, MATH 819/CMPT 881
Assignment 1, Spring 2015.

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This assignment is to be handed in by 2pm Friday January 23rd.
Late penalty: -20% for up to 70 hours late. Zero after that.
For problems involving Maple calculations and Maple programming, please submit a printout of a Maple worksheet.

Question 1 (15 marks): Karatsuba's Algorithm

Reference: Algorithm 4.2 in the Geddes text.

(a) By hand, calculate $(5x^3 + 4x^2 + 3x + 2) \times (3x^3 + 8x^2 + 2x + 9)$ using Karatsuba's algorithm. You will need to do three multiplications involving linear polynomials. Do the first one, $(5x + 4) \times (3x + 8)$ using Karatsuba's algorithm. Do the other two using any method.

(b) Let $T(n)$ be the time it takes to multiply two n digit integers using Karatsuba's algorithm. We will assume (for simplicity) that $n = 2^k$ for some $k > 0$. Then for $n > 1$, we have $T(n) \leq 3T(n/2) + cn$ for some constant $c > 0$ and $T(1) = d$ for some constant $d > 0$.

First show that $3^k = n^{\log_2 3}$. Now solve the recurrence relation and show that $T(n) = (2c + d)n^{\log_2 3} - 2cn$. Show your working.

(c) Show that $T(2n)/T(n) \sim 3$, that is, if we double the length of the integers then the time for Karatsuba's algorithm increases by a factor of 3 (asymptotically).

Question 2 (15 marks): Integer GCD Algorithms

(a) Implement the binary GCD algorithm in Maple as the Maple procedure named BINGCD to compute the GCD of two positive integers a and b. Use the Maple functions `irem(a,b)` and `iquo(a,b)` for dividing by 2.

Your Maple code will have a main loop in it. Each time round the loop please print out current values of (a, b) using the command

```
printf("a=%d  b=%d\n",a,b);
```

so that you and I can see the algorithm working. Test your procedure on the integers $a = 16 \times 3 \times 101$ and $b = 8 \times 3 \times 203$.

(b) Time Maple's `igcd(a,b);` command on random pairs of integers (a, b) of suitable lengths to experimentally determine the time complexity of the algorithm Maple is using. For example, integers of lengths $n = 50000$, 100000, 200000, 400000, etc. decimal digits. Note, the timer in Maple on Windows is inaccurate for timings smaller than 0.01 seconds. Express your answer in $O(f(n))$ notation.

NB: Maple 18 is using a newer version of the GMP integer arithmetic package which has a new algorithm for integer GCD computation. Use Maple 17 or an older version if possible.

Question 3 (20 marks): Gaussian Integers

Let G be the subset of the complex numbers $\mathbb{C}$ defined by $G = \{ x + y\,i : \; x, y \in \mathbb{Z}, \; i = \sqrt{-1}\, \}$. G is called the set of Gaussian integers and is usually denoted by $\mathbb{Z}[i]$.

(a) Why is G an integral domain?
What are the units in G?

Let $a, b \in G$. In order to define the remainder of a divided by b we need a measure $v : G \to \mathbb{N}$ for the size of a non-zero Gaussian integer. We cannot use $v(x + iy) = |x + iy| = \sqrt{x^2 + y^2}$ the the length of the complex number $x + iy$ because it is not an integer valued function. We will instead use the norm $N(x + iy) = x^2 + y^2$ for $v(x + iy)$ which has the following useful properties.

(b) Show that for $a, b \in G$, $N(ab) = N(a)N(b)$ and $N(ab) \geq N(a)$.

(c) Now, given $a, b \in G$, where $b \neq 0$, find a definition for the quotient q and remainder r satisfying $a = b\,q + r$ with $r = 0$ or $v(r) < v(b)$ where $v(x + iy) = x^2 + y^2$. Using your definition calculate the quotient and remainder of $a = 63 + 10i$ divided by $b = 7 + 43i$.

Hint: consider the real and imaginary parts of the complex number a/b and consider how to choose the quotient of a divided b. Note, you must prove that your definition for the remainder r satisfies $r = 0$ or $v(r) < v(b)$. The multiplicative property $N(ab) = N(a)N(b)$ will help you. Now since part (b) implies $v(ab) \geq v(b)$ for non-zero $a, b \in G$, this establishes that G is a Euclidean domain.

(d) Finally write a Maple program REM that computes the remainder r of a divided b using your definition from part (c). Now compute the gcd of $a = 63 + 10i$ and $b = 7 + 43i$ using the Euclidean algorithm and your program. You should get $2 + 3i$ up to multiplication by a unit.

Note, in Maple `I` is the symbol used for the complex number i and you can use the `Re` and `Im` commands to pick off the real and imaginary parts of a complex number. Also, the `round` function may be useful. For example

```
> a := 2+5/3*I;
                         a := 2 + 5/3 I
> Re(a);
                                2
> Im(a);
                               5/3
> round(a);
                             2 + 2 I
```

Question 4 (10 marks): The Extended Euclidean Algorithm

Reference: Algorithm 2.2 in the Geddes text.

Given $a, b \in \mathbb{Z}$, the extended Euclidean algorithm solves $sa + tb = g$ for $s, t \in \mathbb{Z}$ and $g = \gcd(a, b)$. More generally, for $i = 0, 1, ..., n, n+1$ it computes integers (r_i, s_i, t_i) where $r_0 = a, r_1 = b$ satisfying $s_i a + t_i b = r_i$ for $0 \leq i \leq n + 1$.

(a) For $m = 99$, $u = 28$ execute the extended Euclidean algorithm with $r_0 = m$ and $r_1 = u$ by hand. Use the tabular method presented in class that shows the values for r_i, s_i, t_i, q_i. Hence determine the inverse of u modulo m.

(b) Repeat part (a) but this time use the *symmetric remainder*, that is, when dividing a by b choose the quotient q and remainder r are integers satisfying $a = bq+r$ and $-|b/2| \leq r < |b/2|$ instead of $0 \leq r < b$.

Question 5 (20 marks): Integral Domains [MATH 819 students only]

Let S be the subset of the complex numbers $\mathbb{C}$ defined by

$$S \;=\; \{a + b\sqrt{-5} : \; a, b \in \mathbb{Z}\}$$

where addition in S is defined by $(a+b\sqrt{-5})+(c+d\sqrt{-5}) = (a+c)+(b+d)\sqrt{-5}$ and multiplication is defined by $(a + b\sqrt{-5}) \times (c + d\sqrt{-5}) = (ac - 5bd) + (ad + bc)\sqrt{-5}$. Note, since S is a subring of $\mathbb{C}$ then S has no zero-divisors and therefore S is an integral domain.

(a) Show that the only units in S are $+1$ and -1.

(b) Show that S is not a unique factorization domain. Hint: show that the element 21 has two different factorizations into irreducibles. Hint: $1 - 2\sqrt{-5}$ is an irreducible factor of 21. Note: you must show that your factors are irreducible.

(c) Show that the elements $a = 147$ and $b = 21 - 42\sqrt{-5}$ in S have no greatest common divisor. Hint: first show that 21 and $7 - 14\sqrt{-5}$ are both common divisors of a and b.