Inverses

Today: finding inverses quickly.

Euclid's Algorithm.
Runtime.
Euclid's Extended Algorithm.

Refresh

Does 2 have an inverse mod 8? No.

Does 2 have an inverse mod 9? Yes. 5
$2(5) = 10 = 1 \pmod 9$.

Does 6 have an inverse mod 9? No.

x has an inverse modulo m if and only if
$gcd(x, m) > 1$? No.
$gcd(x, m) = 1$? Yes.

Today:
Compute gcd!
Compute Inverse modulo m.

Divisibility...

Notation: $d|x$ means "d divides x" or
$x = kd$ for some integer k.

Fact: If $d|x$ and $d|y$ then $d|(x+y)$ and $d|(x-y)$.
Proof: $d|x$ and $d|y$ or
$x = \ell d$ and $y = kd$

$$\implies x - y = kd - \ell d = (k-\ell)d \implies d|(x-y)$$

$\square$

More divisibility

Notation: $d|x$ means "d divides x" or
$x = kd$ for some integer k.

Lemma 1: If $d|x$ and $d|y$ then $d|y$ and $d| \mod(x,y)$.
Proof:

$$\begin{aligned} \mod(x,y) &= x - \lfloor x/y \rfloor \cdot y \\ &= x - s \cdot y \quad \text{for integer } s \\ &= kd - s\ell d \quad \text{for integers } k,\ell \\ &= (k - s\ell)d \end{aligned}$$

Therefore $d| \mod(x,y)$. And $d|y$ since it is in condition. $\square$

Lemma 2: If $d|y$ and $d| \mod(x,y)$ then $d|y$ and $d|x$.
Proof...: Similar. Try this at home. $\square$.

GCD Mod Corollary: $\gcd(x,y) = \gcd(y, \mod(x,y))$.
Proof: x and y have **same** set of common divisors as x and $\mod(x,y)$ by Lemma.
Same common divisors $\implies$ largest is the same. $\square$

Euclid's algorithm.

GCD Mod Corollary: $\gcd(x,y) = \gcd(y, \mod(x,y))$.

```
gcd (x, y)
  if (y = 0) then
    return x
  else
    return gcd(y, mod(x, y))   ***
```

Theorem: Euclid's algorithm computes the greatest common divisor of x and y if $x \geq y$.

Proof: Use Strong Induction.
Base Case: $y = 0$, "x divides y and x"
$\implies$ "x is common divisor and clearly largest."
Induction Step: $\mod(x,y) < y \leq x$ when $x \geq y$

call in line (***) meets conditions plus arguments "smaller"
and by strong induction hypothesis
computes $\gcd(y, \mod(x,y))$
which is $\gcd(x,y)$ by GCD Mod Corollary. $\square$

Excursion: Value and Size.

Before discussing running time of gcd procedure...

What is the value of 1,000,000?

one million or 1,000,000!

What is the “size” of 1,000,000?

Number of digits: 7.

Number of bits: 21.

For a number x, what is its size in bits?

$$n = b(x) \approx \log_2 x$$

GCD procedure is fast.

Theorem: GCD uses $2n$ "divisions" where n is the number of bits.

Is this good? Better than trying all numbers in $\{2, \ldots y/2\}$?

Check 2, check 3, check 4, check 5 . . . , check $y/2$.

2^{n-1} divisions! Exponential dependence on size!

101 bit number. $2^{100} \approx 10^{30} =$ "million, trillion, trillion" divisions!

$2n$ is much faster! .. roughly 200 divisions.

Algorithms at work.

Trying everything

Check 2, check 3, check 4, check 5 . . . , check $y/2$.

"gcd(x, y)" at work.

```
gcd(700,568)
  gcd(568, 132)
    gcd(132, 40)
      gcd(40, 12)
        gcd(12, 4)
          gcd(4, 0)
            4
```

Notice: The first argument decreases rapidly.
At least a factor of 2 in two recursive calls.

(The second is less than the first.)

Proof.

```
gcd (x, y)
  if (y = 0) then
    return x
  else
    return gcd(y, mod(x, y))
```

Theorem: GCD uses $O(n)$ "divisions" where n is the number of bits.

Proof:

Fact:
First arg decreases by at least factor of two in two recursive calls.

Proof of Fact: Recall that first argument decreases every call.

Case 1: $y \le x/2$, first argument is y $\implies$ true in one recursive call;

Case 2: Will show "$y \ge x/2$" $\implies$ "$mod(x,y) \le x/2$."

$mod(x,y)$ is second argument in next recursive call, and becomes the first argument in the next one.

When $y \ge x/2$, then

$$\lfloor \frac{x}{y} \rfloor = 1,$$

$$\text{mod}\,(x,y) = x - y\lfloor \frac{x}{y} \rfloor = x - y \le x - x/2 = x/2$$

□

After $2\log_2 x = O(n)$ recursive calls, argument x is 1 bit number.
One more recursive call to finish.
1 division per recursive call.
$O(n)$ divisions.

□

Finding an inverse?

We showed how to efficiently tell if there is an inverse.

Extend Euclid's algo to find inverse.

Euclid's GCD algorithm.

```
gcd (x, y)
  if (y = 0) then
    return x
  else
    return gcd(y, mod(x, y))
```

Computes the $\gcd(x,y)$ in $O(n)$ divisions.

For x and m, if $\gcd(x,m) = 1$ then x has an inverse modulo m.

Multiplicative Inverse.

GCD algorithm used to tell **if** there is a multiplicative inverse.

How do we **find** a multiplicative inverse?

Extended GCD

Euclid's Extended GCD Theorem: For any x, y there are integers a, b such that

$$ax + by = \text{gcd}(x, y) = d \qquad \text{where } d = gcd(x, y).$$

"Make d out of sum of multiples of x and y."

What is multiplicative inverse of x modulo m?

By extended GCD theorem, when $\text{gcd}(x, m) = 1$.

$$ax + bm = 1$$
$$ax \equiv 1 - bm \equiv 1 \pmod{m}.$$

So a multiplicative inverse of x if $gcd(a, x) = 1$!!
Example: For $x = 12$ and $y = 35$, $\text{gcd}(12, 35) = 1$.

$$(3)12 + (-1)35 = 1.$$

$a = 3$ and $b = -1$.
The multiplicative inverse of $12 \pmod{35}$ is 3.

Make d out of x and y..?

```
gcd(35,12)
  gcd(12, 11)  ;;  gcd(12, 35%12)
    gcd(11, 1)  ;;  gcd(11, 12%11)
      gcd(1,0)
        1
```

How did gcd get 11 from 35 and 12?
$35 - \lfloor \frac{35}{12} \rfloor 12 = 35 - (2)12 = 11$

How does gcd get 1 from 12 and 11?
$12 - \lfloor \frac{12}{11} \rfloor 11 = 12 - (1)11 = 1$

Algorithm finally returns 1.

But we want 1 from sum of multiples of 35 and 12?

Get 1 from 12 and 11.
$1 = 12 - (1)11 = 12 - (1)(35 - (2)12) = (3)12 + (-1)35$
Get 11 from 35 and 12 and plugin.... Simplify. $a = 3$ and $b = -1$.

Extended GCD Algorithm.

```
ext-gcd(x,y)
  if y = 0 then return(x, 1, 0)
     else
         (d, a, b) := ext-gcd(y, mod(x,y))
         return (d, b, a - floor(x/y)  * b)
```

Claim: Returns (d,a,b): $d = gcd(a,b)$ and $d = ax + by$.
Example: $a - \lfloor x/y \rfloor \cdot b =$
$1 - \lfloor 11/1 \rfloor \cdot 0 = 10 - \lfloor 12/11 \rfloor \cdot 1 = -11 - \lfloor 35/12 \rfloor \cdot (-1) = 3$

```
    ext-gcd(35,12)
      ext-gcd(12, 11)
        ext-gcd(11, 1)
          ext-gcd(1,0)
          return (1,1,0) ;; 1 = (1)1 + (0) 0
        return (1,0,1)   ;; 1 = (0)11 + (1)1
      return (1,1,-1)    ;; 1 = (1)12 + (-1)11
   return (1,-1, 3)      ;; 1 = (-1)35 +(3)12
```

Extended GCD Algorithm.

```
ext-gcd(x,y)
  if y = 0 then return(x, 1, 0)
     else
         (d, a, b) := ext-gcd(y, mod(x,y))
         return (d, b, a - floor(x/y)  * b)
```

Theorem: Returns (d, a, b), where $d = gcd(a, b)$ and

$$d = ax + by.$$

Correctness.

Proof: Strong Induction.[1]
Base: ext-gcd$(x,0)$ returns $(d=x,1,0)$ with $x=(1)x+(0)y$.

Induction Step: Returns (d,A,B) with $d=Ax+By$
Ind hyp: **ext-gcd**$(y,\mod(x,y))$ returns (d^*,a,b) with

$$d^* = ay + b(\mod(x,y))$$

ext-gcd(x,y) calls **ext-gcd**$(y,\mod(x,y))$ so

$$\begin{aligned} d=d^* &= ay+b\cdot(\mod(x,y)) \\ &= ay+b\cdot(x-\lfloor \frac{x}{y} \rfloor y) \\ &= bx+(a-\lfloor \frac{x}{y} \rfloor \cdot b)y \end{aligned}$$

And ext-gcd returns $(d,b,(a-\lfloor \frac{x}{y} \rfloor \cdot b))$ so theorem holds! $\square$

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[1] Assume d is $gcd(x,y)$ by previous proof.

Review Proof: step.

```
ext-gcd(x,y)
  if y = 0 then return(x, 1, 0)
     else
         (d, a, b) := ext-gcd(y, mod(x,y))
         return (d, b, a - floor(x/y)  * b)
```

Recursively: $d = ay + b(x - \lfloor \frac{x}{y} \rfloor \cdot y) \implies d = bx - (a - \lfloor \frac{x}{y} \rfloor b)y$

Returns $(d, b, (a - \lfloor \frac{x}{y} \rfloor \cdot b))$.

Wrap-up

Conclusion: Can find multiplicative inverses in $O(n)$ time!

Very different from elementary school: try 1, try 2, try 3...

$2^{n/2}$

Inverse of $500,000,357$ modulo $1,000,000,000,000$? ≤ 80 divisions.
versus $1,000,000$

Internet Security.
Public Key Cryptography: 512 digits.
512 divisions vs.
$(100000000000000000000000000000000000000000000)^5$ divisions.

Next lecture!