# COS 217: Introduction to Programming Systems

## Assignment 5: Assembly Language Programming, Testing, and Debugging

PRINCETON UNIVERSITY

# Debugging Assembly Language with GDB

Most of the `gdb` commands you already know can be used with assembly language!

- `run`, `break`, `backtrace`, `frame`, `step`, `next`, `continue`, `list`, `print`, `display`, `x`, `watch`, etc.
- Major difference: we'll primarily care about *contents of registers* and *memory pointed to by registers*
- Let's compare...

# GDB: C vs. Assembly Language – Preparation

## C

- Compile with –g flag:

```
gcc217 -g -c myfile.c -o myfile.o
```

## asm

- Add .size directive to the end of every function:

```
    .global myfunc
myfunc:
    ...
    ret
    .size myfunc, (. - myfunc)
```

- Then compile with –g flag:

```
gcc217 -g -c myfile.s -o myfile.o
```

# GDB: C vs. Assembly Language – Running

## C

- From emacs:

```
Esc-x gdb
```

- Or from command line:

```
$ gdb myprog
```

- And then start the program:

```
(gdb) run [arguments]
```

## asm

- Exactly the same

# GDB: C vs. Assembly Language – Where Am I?

## C

- From command-line:

```
(gdb) where (or backtrace or bt)

(gdb) list (or l)
```

- In emacs: code and current location displayed in split-screen

## asm

- Exactly the same

# GDB: C vs. Assembly Language – Printing Variables

## C

- Print contents of variable i:

```
(gdb) print i (or p)
```

- Prints using format appropriate to type of i. Can override format to hex, decimal, character, etc.:

```
(gdb) p/x i
(gdb) p/d i
(gdb) p/c i
```

## asm

- Print contents of register x1:

```
(gdb) p $x1
```

- Can override format:

```
(gdb) p/x $sp
(gdb) p/d $x1
(gdb) p/c $w2
```

- Print contents of all registers:

```
(gdb) info registers (or i r)
```

# GDB: C vs. Assembly Language – Pointers

## C

- Dereference pi and print value:

```
(gdb) p *pi
(gdb) x pi
```

## asm

- Dereference sp+8 and print value:

```
(gdb) p *(int *)($sp+8)
(gdb) x $sp+8
```

- Override data size and format:

```
(gdb) x/bx $sp (byte as hex)
(gdb) x/h $x29 (16-bit halfword)
(gdb) x/wd $x1 (32-bit word as dec)
(gdb) x/g $x10 (64-bit giantword)
(gdb) x/i $pc  (instruction)
```

# GDB: C vs. Assembly Language – Breakpoints

## C

- Set breakpoint:

```
(gdb) break foo.c:37 (or b)
(gdb) b 42 (current file)
(gdb) b 59 if j > 17
(gdb) watch i (break if i changes)
```

- Step to next line of code:

```
(gdb) step (or s)
(gdb) next (or n – step over
            function calls)
```

- Resume execution:

```
(gdb) continue (or c)
(gdb) c 7 (skip next 7 breakpoints)
```

## asm

- Set breakpoint:

```
(gdb) b foo.s:37
(gdb) b 59 if $w2 > 17
(gdb) watch $x1
```

- Step to next instruction:

```
(gdb) stepi (or si)
(gdb) s (instructions == lines)
(gdb) nexti (or ni or next or n)
```

- Resume execution:

```
(gdb) c
(gdb) c 7
```

# GDB: C vs. Assembly Language – Auto-Display

## C

- Print contents of variable i every time gdb resumes control:

```
(gdb) display i (or disp)
```

- Prints using format appropriate to type of i.  Can override format to hex, decimal, character, etc.:

```
(gdb) disp/x i
(gdb) disp/d i
(gdb) disp/c i
```

## asm

- Auto-display contents of register x1:

```
(gdb) disp $x1
```

- Must use cast/dereference syntax to auto-display memory contents:

```
(gdb) disp *(unsigned *)($sp+8)
(gdb) disp/x *(long *)($x1+8*$x2)
```

# Debugging Assembly Language with GDB

Learn to use advanced features – especially conditional breakpoints and displays!

For a full assembly debugging session, watch Lecture 20B from Fall, 2020
(posted on course schedule page)

# Assignment 5 Goals

Apply your knowledge of AARCH64 assembly language!

1. Emulate the compiler: translate C to assembly language
   - Also: practice testing!
2. Beat the compiler: re-implement one critical function to run as quickly as possible

# PART 1

# The wc command

Consider a file named proverb containing the following text:

Learning$_s$is$_s$a$_n$

treasure$_s$which$_n$

accompanies$_s$its$_n$

owner$_s$everywhere.$_n$

--$_s$Chinese$_s$proverb$_n$

@danieltuttle

Then running `wc < proverb` prints the number of lines, words, and characters:

```
5        12        82
```

# Our implementation: `mywc.c`

```
while ((iChar = getchar()) != EOF) {
   lCharCount++;
   if (isspace(iChar)) {
      if (iInWord) {
         lWordCount++;
         iInWord = FALSE;
      }
   } else {
      if (! iInWord)
         iInWord = TRUE;
   }
   if (iChar == '\n')
      lLineCount++;
}
if (iInWord)
   lWordCount++;
printf("%7ld %7ld %7ld\n", lLineCount, lWordCount, lCharCount);
```

# Part 1a Task

Translate `mywc.c` into `mywc.s`

- Generate flattened C code (using conventions in lecture 18) and include as comments!
- Use exactly the same algorithm/logic – don't simplify or optimize
- Use the same 5 `static` variables
- Still call `getchar`, `isspace`, and `printf`
- Don't use the output from `gcc217` (it's convoluted, and it's against the rules)
- Make the code readable, with liberal use of `.equ`

# Part 1b Task

Compose data files (called `mywc*.txt`) that perform the following (see lecture 9):

- boundary tests ("corner cases")
- statement tests (exercise every line of code)
- stress tests (but don't get too wild – not too big, and only ASCII)

Some hints:

- Pretend you're us: design test cases to expose what's wrong
- Write a program that uses `rand()` to generate random characters
- Programatically generated data can also help with boundary tests (which might be hard to generate with an editor)

# PART 2

# Bignum Motivation

Secure communication is enabled by *cryptography*, which is based on the conjectured difficulty of solving certain problems involving big numbers.

Example: discrete logarithm

Let $A = g^a \bmod p$

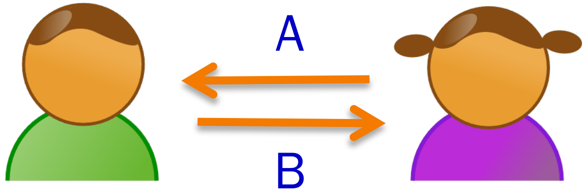
It is believed to be Hard to find a given A, g, and p.

(This might or might not change with quantum computers...)

# Diffie-Hellman Key Exchange

Suppose that Alice creates a secret a and sends $A = g^a \bmod p$ to Bob.

Then Bob creates a secret b and sends $B = g^b \bmod p$ to Alice.




Alice computes $B^a \bmod p = g^{ba} \bmod p$, and Bob computes $A^b \bmod p = g^{ab} \bmod p$

- Alice and Bob now share the same secret number! (To be used e.g. as an encryption key.)
- Any eavesdropper knowing A, B, g, and p can't efficiently compute the secret.

But, to make trial-and-error attacks hard, these computations need numbers much bigger than 32 bits (`int`) or 64 bits (`long`).

# Multiple Precision Arithmetic or "Bignum" Libraries

Emulate arithmetic on quantities bigger than a machine word

Do operations "by hand", except operating on bigger chunks than single digits

- In fact, each "digit" is a machine word – 64 bits in our case
- When adding two "digits", they both range not from 0 to 9, but from 0 to 18 quintillion (-ish)

Example: the GMP library (`gmplib.org`)

Our simplified version: `BigInt`

- Limited to 32768 64-bit words
- No negative numbers
- Only implemented operation: +
- Can't quite do Diffie-Hellman, but our client computes reallyreally large Fibonacci numbers (which grow exponentially)

# BigInt Objects

```
enum {MAX_DIGITS = 32768};

struct BigInt
{
   /* The number of used digits in the BigInt object. The integer 0
      has length 0. This field could be of type int, but then the
      compiler would place padding between this field and the next. */
   long lLength;

   /* The digits comprising the BigInt object. aulDigits[0] stores the
      least significant digit.  The unused digits are set to 0. */
   unsigned long aulDigits[MAX_DIGITS];
};

typedef struct BigInt *BigInt_T;
```

# BigInt Objects

| | | |
|---|---|---|
| 0000ffffbe4d0010 | 0000000000000002 | oBigInt->lLength |
| 0000ffffbe4d0018 | 7777777777777777 | oBigInt->aulDigits[0] |
| 0000ffffbe4d0020 | EEEEEEEEEEEEEEEE | oBigInt->aulDigits[1] |
| 0000ffffbe4d0028 | 0000000000000000 | oBigInt->aulDigits[2] |

HEAP

...

| | | |
|---|---|---|
| STACK | 0000ffffbe4d0010 | oBigInt |

# BigInt_add

```
  0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                  EEEEEEEEEEEEEEEE 7777777777777777
     ----------------------------------------------------
```

# BigInt_add

```
  0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                  EEEEEEEEEEEEEEEE 7777777777777777
     -----------------------------------------------
```

```
  0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                  EEEEEEEEEEEEEEEE 7777777777777777
     -----------------------------------------------
                                       8888888888888888
```

aulDigits[0]

# BigInt_add

```
  0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                  EEEEEEEEEEEEEEEE 7777777777777777
     ---------------------------------------------------
```

```
  0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                  EEEEEEEEEEEEEEEE 7777777777777777
     ---------------------------------------------------
                                       8888888888888888
```

ulCarry

```
                    1
  0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                  EEEEEEEEEEEEEEEE 7777777777777777
     ---------------------------------------------------
                      1111111111111110 8888888888888888
```

aulDigits[1]

# BigInt_add

```
   0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
 + 0x                  EEEEEEEEEEEEEEEE 7777777777777777
      ---------------------------------------------------


   0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
 + 0x                  EEEEEEEEEEEEEEEE 7777777777777777
      ---------------------------------------------------
                                        8888888888888888


                      1
   0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
 + 0x                  EEEEEEEEEEEEEEEE 7777777777777777
      ---------------------------------------------------
                       1111111111111110 8888888888888888
```

```
                  1                1
   0x               FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
 + 0x                                EEEEEEEEEEEEEEEE 7777777777777777
      ----------------------------------------------------------------

                    0000000000000000 1111111111111110 8888888888888888
```

ulCarry

aulDigits[2]

# BigInt_add

```
  0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                  EEEEEEEEEEEEEEEE 7777777777777777
     ----------------------------------------------------
```

```
  0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                  EEEEEEEEEEEEEEEE 7777777777777777
     ----------------------------------------------------
                                       8888888888888888
```

```
                                     1
  0x FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                  EEEEEEEEEEEEEEEE 7777777777777777
     ----------------------------------------------------
                      1111111111111110 8888888888888888
```

```
                      1                1
  0x                   FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                                    EEEEEEEEEEEEEEEE 7777777777777777
     ---------------------------------------------------------------------
                       0000000000000000 1111111111111110 8888888888888888
```

```
                      1                1
  0x                   FFFFFFFFFFFFFFFF 2222222222222222 1111111111111111
+ 0x                                    EEEEEEEEEEEEEEEE 7777777777777777
     ---------------------------------------------------------------------
     0000000000000001 0000000000000000 1111111111111110 8888888888888888
```

`lLength = 4;`

`aulDigits[3]`

# Part 2a: Unoptimized C `BigInt_add` Implementation

Study the given code.

Then build a `fib` program consisting of the files `fib.c`, `bigint.c`, and `bigintadd.c`, *without* the `-D NDEBUG` or `-O` options.

Run the program to compute `fib(250000)`.
In your readme file note the amount of CPU time consumed.

# Part 2b/c: Optimized C `BigInt_add` Implementation

Then build a `fib` program consisting of the files `fib.c`, `bigint.c`, and `bigintadd.c`, *with* the `-D NDEBUG` and `-O` options.

Run the program to compute `fib(250000)`.
In your readme file note the amount of CPU time consumed.

Profile the code with `gprof`. (More on this next lecture.)

# Part 2d/e/f: Implement in Assembly Language

*Suppose, not surprisingly, your* `gprof` *analysis shows that most CPU time is spent executing the* `BigInt_add` *function. In an attempt to gain speed, you decide to code the* `BigInt_add` *function manually in assembly language…*

- Callable from C code!
- Most realistic way of using assembly: you usually won't write entire programs…
- Common to see highly-optimized "kernel" libraries for cryptography, image/video processing, compression, scientific computing, etc.

- Your task: write correct, optimized code, and eventually beat the compiler!

# Part 2d: Translate to Assembly Language

Straightforward translation, as in part 1

- Translate both the `BigInt_larger` and `BigInt_add` functions
- Use exactly the same algorithm/logic – don't simplify or optimize
- Use the same local variables, stored in memory (on the stack)
- Make the code readable, with liberal use of `.equ`
- Test by comparing against `bigintadd.c` using `diff`

# Part 2e: Optimize to use registers, not the stack

Straightforward translation won't beat the compiler. :-(

So, modify your assembly language code to use
callee-saved registers instead of memory
for all parameters and local variables (see lecture 19).

# Part 2f (Challenge Portion): Optimize All You Want

Start with the following optimizations:

# Part 2f (Challenge Portion): Optimize All You Want

Start with the following optimizations:

- Use the *guarded loop* pattern (Pyeatt/Ughetta Ch. 5, Sec. 3.2)

**Original C**

```
while (expr) {
   statement1;
   ...
   statementN;
}
```

**Basic Flattened C**

```
loop1:
   if (! expr) goto endloop1;
   statement1;
   ...
   statementN;
   goto loop1;
endloop1:
```

**Guarded Loop Pattern**

```
if (! expr) goto endloop1;
loop1:
   statement1;
   ...
   statementN;
   if (expr) goto loop1;
endloop1:
```

Pro: 1 fewer instruction per iteration of the loop
Con: Duplicate code to compute and test !expr and expr

# Part 2f (Challenge Portion): Optimize All You Want

Start with the following optimizations:

- Use the *guarded loop* pattern (Pyeatt/Ughetta Ch. 5, Sec. 3.2)
- *Inline* the call of the `BigInt_larger` function

# Part 2f (Challenge Portion): Optimize All You Want

Start with the following optimizations:

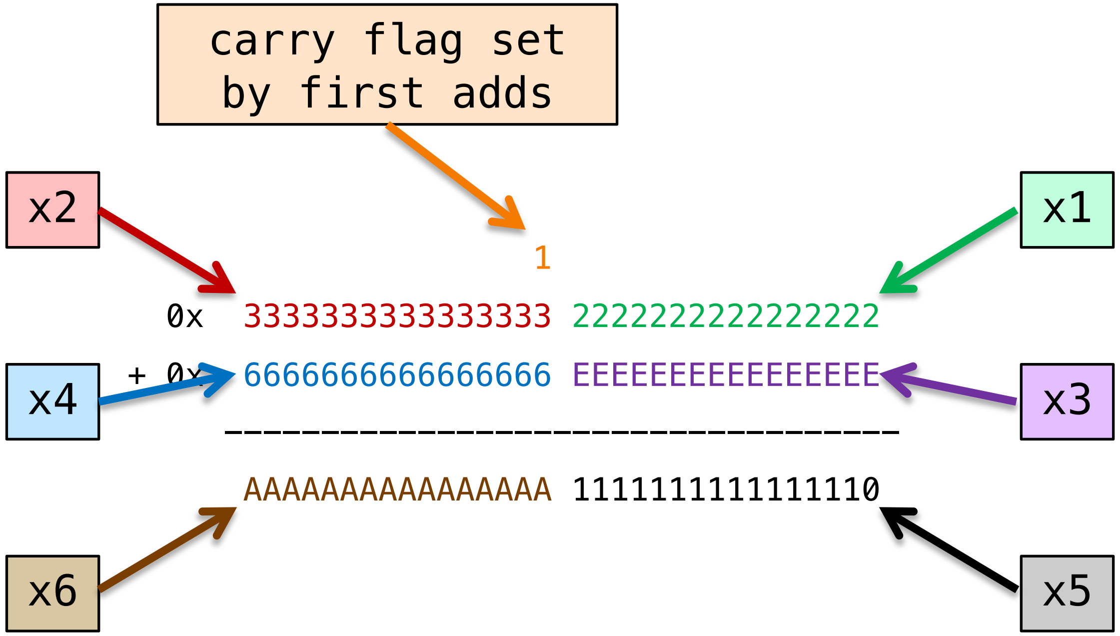
- Use the *guarded loop* pattern (Pyeatt/Ughetta Ch. 5, Sec. 3.2)
- *Inline* the call of the `BigInt_larger` function
- Use the `adcs` ("add with carry and set condition flags") instruction

```
                      1
    0x  3333333333333333 2222222222222222
  + 0x  6666666666666666 EEEEEEEEEEEEEEEE
       ----------------------------------
        AAAAAAAAAAAAAAAA 1111111111111110
```

# Part 2f (Challenge Portion): Optimize All You Want

Start with the following optimizations:

- Use the *guarded loop* pattern (Pyeatt/Ughetta Ch. 5, Sec. 3.2)
- *Inline* the call of the `BigInt_larger` function
- Use the `adcs` ("add with carry and set condition flags") instruction




```
adds x5, x1, x3
adcs x6, x2, x4
```

# Part 2f (Challenge Portion): Optimize All You Want

Start with the following optimizations:

- Use the *guarded loop* pattern (Pyeatt/Ughetta Ch. 5, Sec. 3.2)
- *Inline* the call of the `BigInt_larger` function
- Use the `adcs` ("add with carry and set condition flags") instruction

Then feel free to implement any additional optimizations!

Beating the compiler is totally realistic!

But, this part is challenging. Don't let it consume all your time.
We will not think unkindly of you if you decide not to do it.



Reminder: this is a *partnered* assignment.