A brief intro to

CS61

Systems Programming and Machine Organization

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December 3, 2008

CS61

Fall 2009: Tuesday/Thursday 2:30-4:00

Prerequisites: CS50 (or C programming experience)

Can be used for CS concentration breadth requirement (“middle digit”)

Can be used for CS secondary area requirement

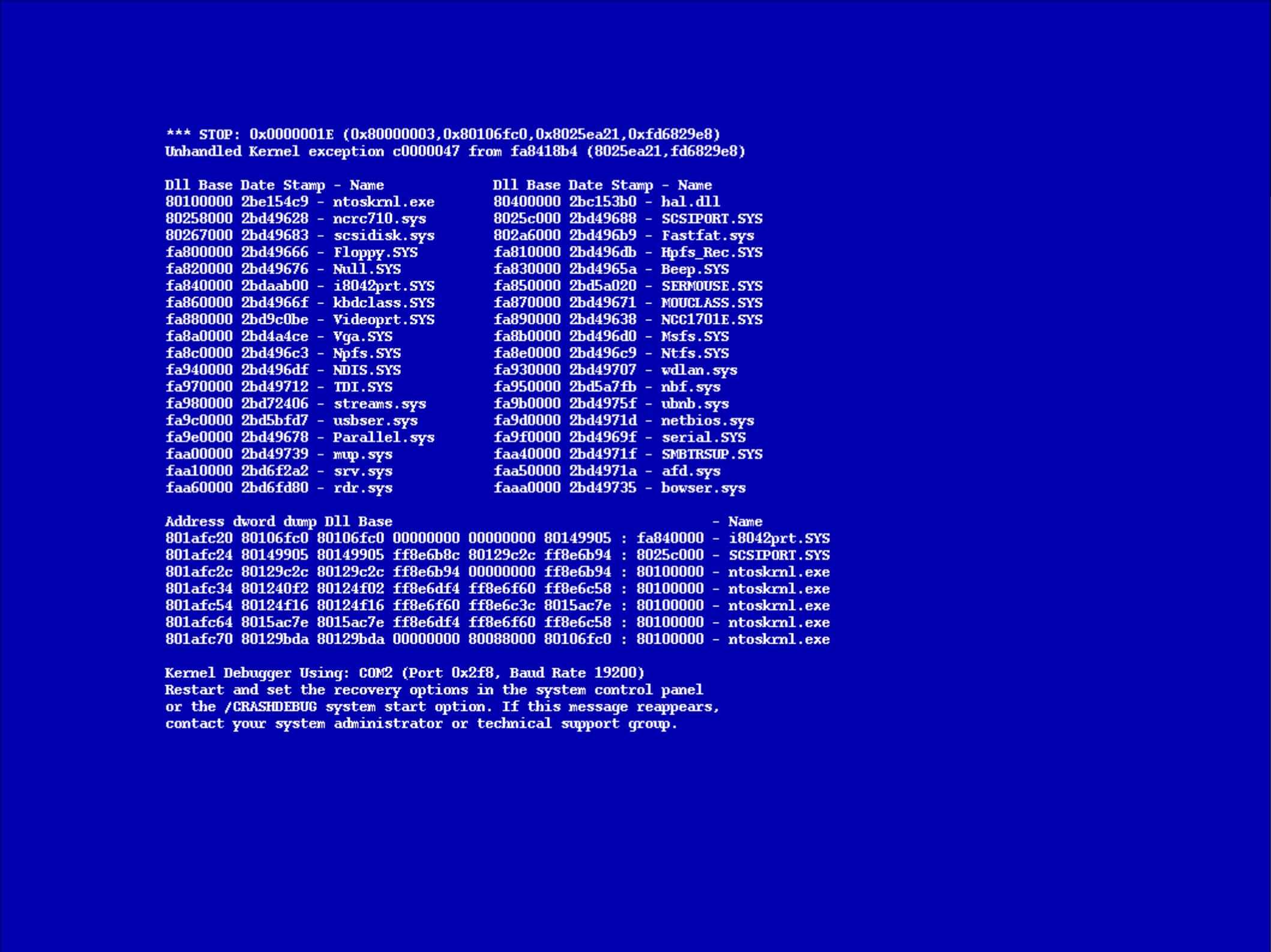
You can, and should, take both CS51 and CS61 at the same time!

What is CS61 all about?

- Revealing the mystery of how machines really work!
- Getting “under the hood” of programming at the machine level
- Understanding what affects the performance of your programs:
  - Processor architecture
  - Caching and memory management
  - Processes, threads, and synchronization
- Writing rock solid (and fast) systems code

Why CS61?

- Huge gap between the *concepts* of programming and the *reality*
- This gap is more profound when you start programming in higher-level languages: Java, C++, Scheme, etc.
- Need to understand how machines really work to grasp:
  - Operating Systems
  - Databases
  - Processor Architecture
  - Compilers
  - Networks
- ... and even just to be a good programmer, even if you don't become a Computer Scientist.


*** STOP: 0x0000001E (0x80000003,0x80106fc0,0x8025ea21,0xfd6829e8)
Unhandled Kernel exception c0000047 from fa8418b4 (8025ea21,fd6829e8)
Dll Base Date Stamp - Name
80100000 2be154c9 - ntoskrnl.exe
80258000 2bd49628 - ncrc710.sys
80267000 2bd49683 - scsidisk.sys
fa800000 2bd49666 - Floppy.SYS
fa820000 2bd49676 - Null.SYS
fa840000 2bdaab00 - i8042prt.SYS
fa860000 2bd4966f - kbdclass.SYS
fa880000 2bd9c0be - Videoprt.SYS
fa8a0000 2bd4a4ce - Vga.SYS
fa8c0000 2bd496c3 - Npfs.SYS
fa940000 2bd496df - NDIS.SYS
fa970000 2bd49712 - TDI.SYS
fa980000 2bd72406 - streams.sys
fa9c0000 2bd5bfd7 - usbser.sys
fa9e0000 2bd49678 - Parallel.sys
faa00000 2bd49739 - mup.sys
faa10000 2bd6f2a2 - srv.sys
faa60000 2bd6fd80 - rdr.sys
Dll Base Date Stamp - Name
80400000 2bc153b0 - hal.dll
8025c000 2bd49688 - SCSIPORT.SYS
802a6000 2bd496b9 - Fastfat.sys
fa810000 2bd496db - Hpfs_Rec.SYS
fa830000 2bd4965a - Beep.SYS
fa850000 2bd5a020 - SERMOUSE.SYS
fa870000 2bd49671 - MOUCLASS.SYS
fa890000 2bd49638 - NCC1701E.SYS
fa8b0000 2bd496d0 - Msfs.SYS
fa8e0000 2bd496c9 - Ntfs.SYS
fa930000 2bd49707 - wdlan.sys
fa950000 2bd5a7fb - nbf.sys
fa9b0000 2bd4975f - ubnb.sys
fa9d0000 2bd4971d - netbios.sys
fa9f0000 2bd4969f - serial.SYS
faa40000 2bd4971f - SMBTRSUP.SYS
faa50000 2bd4971a - afd.sys
faaa0000 2bd49735 - bowser.sys
Address dword dump Dll Base - Name
801afc20 80106fc0 80106fc0 00000000 00000000 80149905 : fa840000 - i8042prt.SYS
801afc24 80149905 80149905 ff8e6b8c 80129c2c ff8e6b94 : 8025c000 - SCSIPORT.SYS
801afc2c 80129c2c 80129c2c ff8e6b94 00000000 ff8e6b94 : 80100000 - ntoskrnl.exe
801afc34 801240f2 80124f02 ff8e6df4 ff8e6f60 ff8e6c58 : 80100000 - ntoskrnl.exe
801afc54 80124f16 80124f16 ff8e6f60 ff8e6c3c 8015ac7e : 80100000 - ntoskrnl.exe
801afc64 8015ac7e 8015ac7e ff8e6df4 ff8e6f60 ff8e6c58 : 80100000 - ntoskrnl.exe
801afc70 80129bda 80129bda 00000000 80088000 80106fc0 : 80100000 - ntoskrnl.exe
Kernel Debugger Using: COM2 (Port 0x2f8, Baud Rate 19200)
Restart and set the recovery options in the system control panel
or the /CRASHDEBUG system start option. If this message reappears,
contact your system administrator or technical support group.

How many times have you seen this?

```
% gcc -o myawesomeprogram map.c

% ./myawesomeprogram
segmentation fault – core dumped

%
```

```
% gdb myawesomeprogram core

(gdb) where
#0 0x00001fea in main ()

(gdb) disass
Dump of assembler code for function main:
0x00001fc6 <main+0>:    push   %ebp
0x00001fc7 <main+1>:    mov    %esp,%ebp
0x00001fc9 <main+3>:    sub    $0x28,%esp
0x00001fcc <main+6>:    movl   $0x200,(%esp)
0x00001fd3 <main+13>:   call   0x3005 <dyld_stub_malloc>
0x00001fd8 <main+18>:   mov    %eax,-0x10(%ebp)
0x00001fdb <main+21>:   movl   $0x0,-0xc(%ebp)
0x00001fe2 <main+28>:   jmp    0x1ff2 <main+44>
0x00001fe4 <main+30>:   mov    -0xc(%ebp),%eax
0x00001fe7 <main+33>:   add    -0x10(%ebp),%eax
0x00001fea <main+36>:   movb   $0x42,(%eax)
0x00001fed <main+39>:   lea    -0xc(%ebp),%eax
0x00001ff0 <main+42>:   incl   (%eax)
0x00001ff2 <main+44>:   cmpl   $0x270ffff,-0xc(%ebp)
0x00001ff9 <main+51>:   jle    0x1fe4 <main+30>
0x00001ffb <main+53>:   leave
0x00001ffc <main+54>:   ret
End of assembler dump.
```

Hacking into my account...

- Say I left a program in my home directory that would run a shell as "mdw" if you gave it the right password.

```
% cd /home/mdw
% ./mdwshell
% Enter the password: *********
Congratulations! Running shell...

$ whoami
mdw
```

How would you figure it out?

- Brute force guess? No dice ...

```
% cd /home/mdw
% ./mdwshell
% Enter the password: lameguess
Sorry, wrong!
Emailing President Faust...

%
```

How would you figure it out?

- What if you could read the executable file?

```
% cat mdwshell
ELF@44 ($!444ààüüüüüü$LÐÐ(((
Qåtd/lib/ld-linux.so.2GNU)¬KãÀgUa
Hy\²0B)óA9U 6N@¨;
__gmon_start__libc.so.6_IO_stdin_
usedfflushexeclputnàinprintffgets
stdoutmalloc__libc_start_mainGLIB
C_2.0ii UåSìè[ÃXüÿÿÿÒtèèù
´X[ÉÃÿ5èÿ%ìÿ%ðhéàÿÿÿÿ%ôéÐÿÿÿÿ%øhé
Àÿÿÿÿÿ%ühé°ÿÿÿÿÿ%hé ÿÿÿÿ%h(éÿÿÿÿh0é
€ÿÿÿÿÿ%h8épÿÿÿÿ1í^ääðPTRhðhQVhGèÿ
```

How would you figure it out?

- What if you could read the executable file?

```
% od -x mdwshell
0000000 457f 464c 0101 0001 0000 0000 0000 0000
0000020 0002 0003 0001 0000 8440 0804 0034 0000
0000040 0f8c 0000 0000 0000 0034 0020 0007 0028
0000060 0024 0021 0006 0000 0034 0000 8034 0804
0000100 8034 0804 00e0 0000 00e0 0000 0005 0000
0000120 0004 0000 0003 0000 0114 0000 8114 0804
0000140 8114 0804 0013 0000 0013 0000 0004 0000
0000160 0001 0000 0001 0000 0000 0000 8000 0804
```

Disassembly?

```
% objdump -d mdwshell
...
080484f0 <check_password>:
 80484f0:       55                      push   %ebp
 80484f1:       89 e5                   mov    %esp,%ebp
 80484f3:       83 ec 14                sub    $0x14,%esp
 80484f6:       a1 14 98 04 08          mov    0x8049814,%eax
 80484fb:       89 45 fc                mov    %eax,-0x4(%ebp)
 80484fe:       eb 21                   jmp    8048521
 8048500:       8b 45 08                mov    0x8(%ebp),%eax
 8048503:       0f b6 10                movzbl (%eax),%edx
 8048506:       8b 45 fc                mov    -0x4(%ebp),%eax
 8048509:       0f b6 00                movzbl (%eax),%eax
 804850c:       38 c2                   cmp    %al,%dl
 804850e:       74 09                   je     8048519
 8048510:       c7 45 ec 00 00 00 00    movl   $0x0,-0x14(%ebp)
 8048517:       eb 29                   jmp    8048542
 8048519:       83 45 08 01             addl   $0x1,0x8(%ebp)
 804851d:       83 45 fc 01             addl   $0x1,-0x4(%ebp)
 8048521:       8b 45 08                mov    0x8(%ebp),%eax
 8048524:       0f b6 00                movzbl (%eax),%eax
 8048527:       0f be c0                movsbl %al,%eax
  ...
```

Disassembly

```
push   %ebp
mov    %esp,%ebp
sub    $0x14,%esp
mov    0x8049814,%eax
mov    %eax,-0x4(%ebp)
jmp    8048521
mov    0x8(%ebp),%eax
```

- Put the ebp register on the stack
- Copy stack pointer to ebp register
- Subtract 20 bytes from stack pointer
- Move 0x8049814 to eax register
- Move eax register to local variable
- Jump to address 0x804521
- Copy 2nd argument to eax register

Disassembly

```
push   %ebp
mov    %esp,%ebp
sub    $0x14,%esp
mov    0x8049814,%eax
mov    %eax,-0x4(%ebp)
jmp    8048521
mov    0x8(%ebp),%eax
```

- Put the ebp register on the stack
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- Copy 2nd argument to eax register

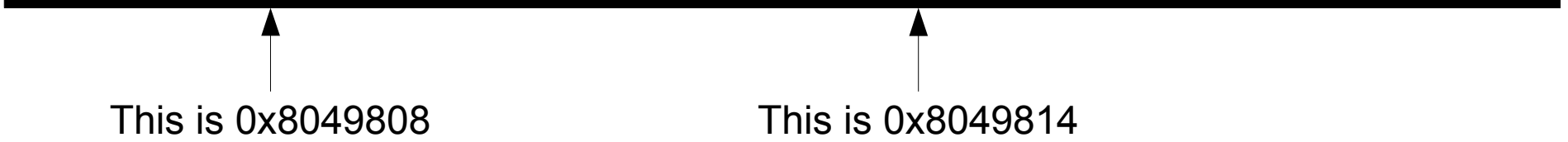
- Hmmm ... seems kind of complex.
  - Until you take CS61 that is...
- What's this?

```
mov    0x8049814,%eax
```

Looks interesting.

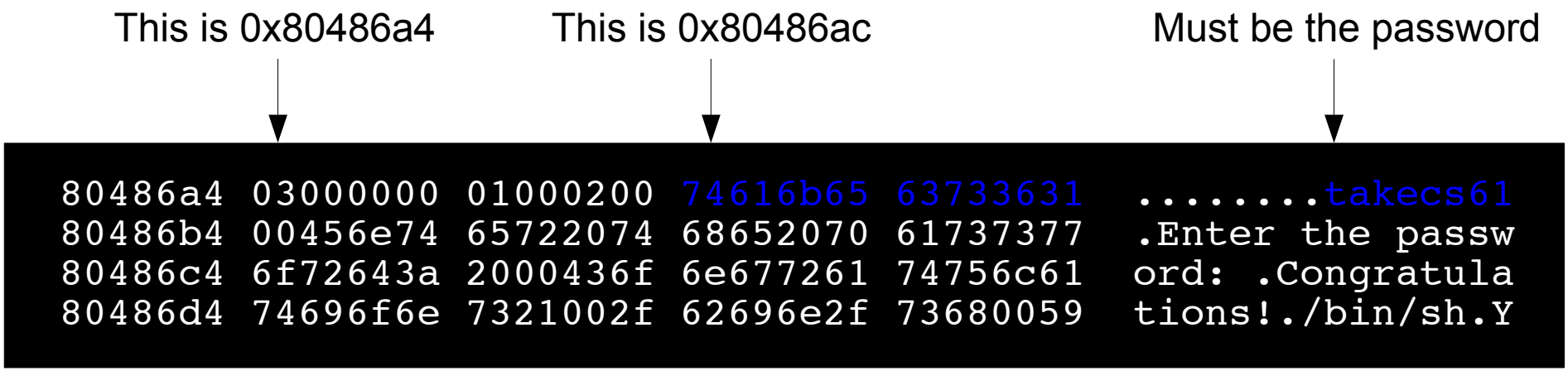
Disassembly

```
% objdump -s mdwshell
...
Contents of section .data:
 8049808 00000000 00000000 00970408 ac860408  ................
```



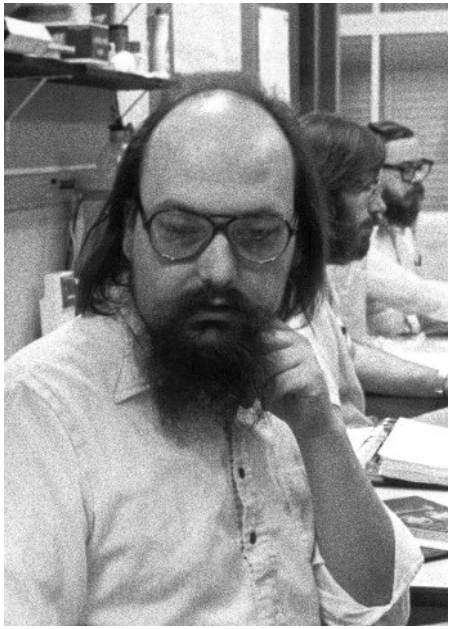
- This is what the “check_password” routine is looking at. How do we read it?
- Well, the x86 is a **little-endian** processor...
  - Meaning, a four-word byte is stored with the **least** significant byte **first!**
  - So, `ac 86 04 08` == 0x080486ac
  - Hmm, that looks like another memory address....

Disassembly



Ken Thompson's Compiler Hack

- Ken Thompson – Co-inventor of UNIX
- Won Turing Award in 1983 (with Dennis Ritchie)
- During his award lecture, made a stunning admission...



Thompson's Compiler Hack

- Early days of UNIX: Thompson hacked the “login” program
  - Would accept a “magic” password to let him login on any UNIX system
  - Really helpful for debugging ...
- Problem: The source code for “login.c” was widely distributed
  - The whole system was “open source” (before we had that term...)
  - So, anyone could find the backdoor code!
- So, he hacked the C compiler...
  - C compiler would recognize that it was compiling “login.c”
  - Insert the backdoor code in at compile time

Thompson's Compiler Hack

- Now the backdoor was in the compiler code.
  What if someone read that?
- He hacked the ***compiler*** to recognize when it was compiling ***itself***
  - The compiler was itself implemented in C.
  - (Chicken and egg problem: How did they write the first C compiler?)
- The compiler would insert the backdoor code into itself!
  - So when the compiler compiles itself, it would insert the backdoor code to recognize when it was compiling login.c, to insert the backdoor code to check for the magic password. Got it?
- He then deleted the original compiler source code.
  - The backdoor could only be found in the ***binary!***

Why take CS61?

- Learn how machines really work.
  - Use gdb and objdump like an expert.
- Debug the hardest (and most interesting) bugs.
  - Stuff that only makes sense when you can read assembly.
- Hacking binaries for fun and profit.
  - How did the iPhone get jailbroken? The Code Red virus spread so quickly?
- Measure and improve the performance of your programs.
  - Understand memory hierarchies, processor pipelines, and parallelism.
- Write concurrent, multi-threaded programs like a pro.
  - The basis for every application and server on the Internet today.

Er, this sounds really hard...

- CS61 is **not** intended to be a heavy workload course.
  - Challenging, but fun.
  - Intended for everyone who has taken CS50 – not just CS concentrators
- Five lab assignments – can work in pairs:
  - 1) Defusing a binary bomb
  - 2) Hacking a buffer overrun bug
  - 3) Implementing dynamic memory allocation
  - 4) Writing your own UNIX shell
  - 5) Building a concurrent Internet service.
- One midterm, and a final. Both take home. That's it.

Topics to be covered

- Intel x86 assembly language programming
  - Registers, memory, control flow, procedures, data structures
- Performance measurement and program optimization
- Linking and loading
- Memory hierarchy, caching, and dynamic memory allocation
- UNIX systems programming: files, pipes, signals, processes
- Threads and synchronization
- UNIX sockets programming
- Implementing concurrent servers

Questions?

- Email me! mdw@eecs.harvard.edu
- Or drop by Maxwell Dworkin 233