Basic functionality of processors

- Execute machine code
  - Sequence of instructions (simple operations)
    - Arithmetic, logic, conditional, jumps, branches, etc.
- Access memory and peripherals
  - Using registers for internal data storage
  - Using memory management unit
    - Translating virtual addresses to physical addresses
Machine Code

IA-32 machine code
Sequence of bytes stored in memory and processed by the processor

IA-32 instruction mnemonics (AT&T syntax)
Code written by hand or compiled by a high-level language compiler

Assembler compiles it to machine code
### SPARC V9 machine code

All instructions are exactly 4 bytes long.

#### Opcode

<table>
<thead>
<tr>
<th>Opcode</th>
<th>Instruction</th>
<th>Register</th>
<th>Displacement</th>
<th>Dereference</th>
</tr>
</thead>
<tbody>
<tr>
<td>86 03 a7 ff</td>
<td>add %sp, 0x7ff, %g3</td>
<td>%g3</td>
<td>0x7ff</td>
<td>%sp</td>
</tr>
<tr>
<td>89 57 c0 00</td>
<td>rdpr %ver, %g4</td>
<td>%g4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>82 10 3f ff</td>
<td>mov -1, %g1</td>
<td>%g1</td>
<td>0x1</td>
<td></td>
</tr>
<tr>
<td>83 28 70 0e</td>
<td>sllx %g1, 0xe, %g1</td>
<td>%g1</td>
<td>0xe</td>
<td>%g1</td>
</tr>
<tr>
<td>86 08 c0 01</td>
<td>and %g3, %g1, %g3</td>
<td>%g3, %g1, %g3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c4 58 e0 18</td>
<td>ldx [ %g3 + 0x18 ], %g2</td>
<td>%g2</td>
<td>0x18</td>
<td>%g3</td>
</tr>
<tr>
<td>81 c3 e0 08</td>
<td>retl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c8 70 a4 78</td>
<td>stx %g4, [ %g2 + 0x478 ]</td>
<td>%g4</td>
<td>0x478</td>
<td>%g2</td>
</tr>
</tbody>
</table>
Binary Interoperability

- Many degrees of freedom for machine code
  - How to call subroutines (functions)?
  - How to pass arguments to functions?
  - How to pass return values from functions?
  - Where to store local variables?

- Application Binary Interface
  - Set of conventions defining machine code usage
  - Interoperability between compilers, assemblers, linkers, libraries, user space and operating system, etc.
Registers

- **Small and fast static memory**
  - Integral part of most processors
  - Addressed usually by small index
    - In assembler mnemonics by a name (eax, rflags, g7, etc.)
  - Usually word-sized (8, 16, 32, 64, 128 bits)
- **Basic taxonomy**
  - System Registers
  - Application Registers
    - General Purpose Registers (accumulator, base, source, destination, etc.)
    - Special Registers (flags, etc.)
**General Purpose Registers**

- **For general computation**
  - Values fetched from memory, results of calculations, addresses, etc.
  - Defined by the architecture of the processor
    - **IA-32**
      - `eax, ebx, ecx, edx, esi, edi`
    - **AMD64**
      - `rax, rbx, rcx, rdx, rsi, rdi, r8, ..., r15`
    - **SPARC V9**
      - `r0, ..., r31` (but it's more complicated)
Volatile GPRs

- **Scratch, Caller-Saved**
  - Defined by the ABI
  - When calling a function, these registers can be right away **used by the callee**
  - If the **caller** stores important values in these registers (and wants to preserve the values across function calls), it **must save** them before it calls the callee
Non-Volatile GPRs

- Preserved, Callee-Saved
  - Defined by the ABI
  - When calling a function, the **callee must save the original values** before it can use these registers and **restore the original values** before returning to the caller
  - The caller does not need to care about these registers, the **values are preserved for the caller**
Memory Stack

- **Stack**
  - Generic data structure for storing items of the same kind
    - A queue with LIFO (last-in first-out) semantics
    - Two basic operations
      - Push (add an item to the stack)
      - Pop (remove the last inserted item from the stack)

- **Memory Stack**
  - A stack stored physically as an array of items in memory
Memory Stack (2)

item 1

push

stack top

stack bottom
Memory Stack (2)

- Item 2
- Push
- Stack top
- Stack bottom
- Item 1
Memory Stack (2)
Memory Stack (2)

- Stack top
- Stack bottom

item 1
Memory Stack (3)

- **Storing register values**
  - Return addresses, local variables, etc.
  - Stack top is addressed by **stack pointer** (register)
    - Aligned, usually grows towards lower addresses
      - Push decreases the pointer
      - Pop increases the pointer
  - All items are also accessible directly
    - Stack pointer as a base address, plus displacement

```
<table>
<thead>
<tr>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0fe4</td>
</tr>
<tr>
<td>0x0fe8</td>
</tr>
<tr>
<td>sp=0x0fec</td>
</tr>
<tr>
<td>0x00000000</td>
</tr>
<tr>
<td>0x00000001</td>
</tr>
<tr>
<td>0xaaee9988</td>
</tr>
<tr>
<td>0xdeadbeef</td>
</tr>
<tr>
<td>0x0ff8</td>
</tr>
<tr>
<td>0x0ff4</td>
</tr>
<tr>
<td>0x0ff0</td>
</tr>
<tr>
<td>0x0fec</td>
</tr>
<tr>
<td>0x0fe8</td>
</tr>
<tr>
<td>0x0ff4</td>
</tr>
<tr>
<td>0x0ff0</td>
</tr>
<tr>
<td>0x0ff8</td>
</tr>
<tr>
<td>0x0ffc</td>
</tr>
<tr>
<td>0x1000</td>
</tr>
<tr>
<td>0x12345678</td>
</tr>
</tbody>
</table>
```
Implicit stack support

- The processor has inherent support for the memory stack
  - Automatically pushes the return address onto the memory stack when calling a subroutine (function)
  - Pops the return address from the memory stack when returning from the function
  - Usually provides dedicated instructions (PUSH, POP)
  - Hard-wired stack pointer register
  - IA-32, AMD64
Explicit stack

- The processor does not provide any dedicated primitives to work with the memory stack
  - The code operates with the memory stack as with any other memory area (by hand)
    - PUSH: Decrease the stack pointer and store the value
    - POP: Fetch the value and increase the stack pointer
    - Stack pointer register is defined by ABI (not hard-wired)
  - Return address is stored in a dedicated register
    - Optionally pushed to the stack by hand
  - MIPS, SPARC V9 (in flat mode)
Memory Stack (6)

- **Stack pointer**
  - Points to the last pushed item
    - Except for possible stack pointer bias
  - Stored in a GPR
    - Either defined by the architecture or by the ABI

- **Stack frame**
  - Items on the stack that belong to a single function

- **Frame pointer**
  - Optional pointer pointing to the beginning of the current stack frame
    - Can be stored in a GPR (defined by the ABI)
Stack Frame

- **Inserted on the stack when a subroutine is called**

  - **Contents**
    - Pointer to the previous stack frame (of the caller)
    - Values of preserved registers (if needed)
    - Local variables
    - Ad hoc values (if any)
      - Other preserved registers, stack allocations, etc.
    - When calling other subroutine
      - Outgoing arguments and return address (if any)

  - **Defined by the ABI**
    - Who creates the stack frame (on subroutine entry)
    - Who removes the stack frame (on subroutine exit)
Stack Frame (2)

Before call
(caller with no local data)

During call
(before callee acquires control)
Stack Frame (3)

During call
(before callee acquires control)

After call
(callee has control)
Consecutive stack frames

- Organized in a linked list
- Linked using the pointer to the previous stack frame
  - Embedded in any given stack frame
- The printout of this linked list is a stack trace
Stack Trace

```c
int c(int i) { return i; }
int b(int i) { return c(i); }
int a(int i) { return b(i); }
int main(int argc, char *argv[]) {
    return a(argc);
}
```

Stack frame address

- `0x46b78: c+3(1, 0, 0, fefa3000)`
- `0x46b98: b+0x11(1, 80509e4, feff350f, 8)`
- `0x46bb8: a+0x11(1, feef31c, 29, fefab85c)`
- `0x46bec: main+0x27(1, 8046c10, 8046c18)`
- `0x46c04: _start+0x80(1, 8046d60, 0, 8046d68, 8046d8a, 8046da1)`

Return address

- (not reliable, must confront with reality)
## Stack Frames

<table>
<thead>
<tr>
<th>Address</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x8046b78</td>
<td>0x8046b98</td>
</tr>
<tr>
<td>0x8046b7c</td>
<td>b+0x11</td>
</tr>
<tr>
<td>0x8046b80</td>
<td>1</td>
</tr>
<tr>
<td>0x8046b84</td>
<td>0</td>
</tr>
<tr>
<td>0x8046b88</td>
<td>0</td>
</tr>
<tr>
<td>0x8046b8c</td>
<td>0xfefa3000</td>
</tr>
<tr>
<td>0x8046b90</td>
<td>0x8047ff3</td>
</tr>
<tr>
<td>0x8046b94</td>
<td>libc.so.1`_fpstart</td>
</tr>
<tr>
<td>0x8046b98</td>
<td>0x8046bb8</td>
</tr>
<tr>
<td>0x8046b9c</td>
<td>a+0x11</td>
</tr>
<tr>
<td>0x8046ba0</td>
<td>1</td>
</tr>
<tr>
<td>0x8046ba4</td>
<td>0x80509e4</td>
</tr>
<tr>
<td>0x8046ba8</td>
<td>ld.so.1`dbg_desc</td>
</tr>
<tr>
<td>0x8046bac</td>
<td>8</td>
</tr>
<tr>
<td>0x8046bb0</td>
<td>1</td>
</tr>
<tr>
<td>0x8046bb4</td>
<td>0</td>
</tr>
<tr>
<td>0x8046bb8</td>
<td>0x8046bec</td>
</tr>
<tr>
<td>0x8046bbc</td>
<td>main+0x27</td>
</tr>
<tr>
<td>0x8046bc0</td>
<td>1</td>
</tr>
<tr>
<td>0x8046bc4</td>
<td>libc.so.1`_fpstart+0x2c</td>
</tr>
<tr>
<td>0x8046bc8</td>
<td>0x29</td>
</tr>
<tr>
<td>0x8046bcc</td>
<td>libc.so.1`_fp_hw</td>
</tr>
<tr>
<td>0x8046bd0</td>
<td>0x133f</td>
</tr>
<tr>
<td>0x8046bd4</td>
<td>0x8050cf6</td>
</tr>
<tr>
<td>0x8046bd8</td>
<td>0x8060d5c</td>
</tr>
<tr>
<td>0x8046bdc</td>
<td>0x8046bcc</td>
</tr>
<tr>
<td>0x8046be0</td>
<td>0x8046bec</td>
</tr>
<tr>
<td>0x8046be4</td>
<td>_init+0x1a</td>
</tr>
<tr>
<td>0x8046be8</td>
<td>0xfeffb7dc</td>
</tr>
<tr>
<td>0x8046bec</td>
<td>0x8046c04</td>
</tr>
</tbody>
</table>
Stack Frames

**c()'s frame**
- 0x8046b78: 0x8046b98

**a()'s frame**
- 0x8046b9c: a+0x11
- 0x8046ba0: 1
- 0x8046ba4: 0x80509e4
- 0x8046ba8: ld.so.1`dbg_desc
- 0x8046bac: 8
- 0x8046bb0: 1
- 0x8046bb4: 0
- 0x8046bb8: 0x8046bec

**b()'s frame**
- 0x8046b7c: b+0x11
- 0x8046b80: 1
- 0x8046b84: 0
- 0x8046b88: 0
- 0x8046b8c: 0xfefa3000
- 0x8046b90: 0x8047ff3
- 0x8046b94: libc.so.1`_fpstart
- 0x8046b98: 0x8046bb8

**main()'s frame**
- 0x8046bbc: main+0x27
- 0x8046bc0: 1
- 0x8046bc4: libc.so.1`_fpstart+0x2c
- 0x8046bc8: 0x29
- 0x8046bcc: libc.so.1`_fp_hw
- 0x8046bd0: 0x133f
- 0x8046bd4: 0x8050cf6
- 0x8046bd8: 0x8060d5c
- 0x8046bcd: 0x8046bcc
- 0x8046be0: 0x8046bec
- 0x8046be4: _init+0x1a
- 0x8046be8: 0xfeffb7dc
- 0x8046bec: 0x8046c04
Stack Frames

c()'s frame
0x8046b78: 0x8046b98

b()'s frame
0x8046b7c: b+0x11
0x8046b80: 1
0x8046b84: 0
0x8046b88: 0
0x8046b8c: 0xfefa3000
0x8046b90: 0x8047ff3
0x8046b94: libc.so.1`_fpstart
0x8046b98: 0x8046bb8

a()'s frame
0x8046b9c: a+0x11
0x8046ba0: 1
0x8046ba4: 0x80509e4
0x8046ba8: ld.so.1`dbg_desc
0x8046bac: 8
0x8046bb0: 1
0x8046bb4: 0
0x8046bb8: 0x8046bec

main()'s frame
0x8046bbc: main+0x27
0x8046bc0: 1
0x8046bc4: libc.so.1`_fpstart+0x2c
0x8046bc8: 0x29
0x8046bcc: libc.so.1`_fp_hw
0x8046bd0: 0x133f
0x8046bd4: 0x8050cf6
0x8046bd8: 0x8060d5c
0x8046bdc: 0x8046bcc
0x8046be0: 0x8046bec
0x8046be4: _init+0x1a
0x8046be8: 0xfeff7dc
0x8046bec: 0x8046c04
Prologue and Epilogue

- Stack frame bookkeeping code
  - Function code generated by the compiler
  - **Prologue**
    - Sequence of instructions at the beginning of a function
    - Creates the stack frame and saves the used preserved registers
  - **Epilogue**
    - Sequence of instructions before the function returns
    - Restores the saved preserved registers and destroys the stack frame
Stack Optimizations

- **Unusual stack frame constriction**
  - For speed optimization
  - Obfuscation of the stack trace
  - **Leaf optimization**
    - Leaf functions don't create their own stack frame and reuse the caller's stack frame
  - **Tail call optimization**
    - If a function is called from the tail of the current function, the caller's stack frame is recycled
  - **Function inlining**
    - The function call is replaced by direct inclusion of the code of the callee
In the following example ...

- Functions `main()`, `a()`, `b()`, `c()` compiled with various compiler optimization levels
- Breakpoint in the business code of `c()`
  - Avoiding the prologue and epilogue of `c()`
- Displaying the stack trace when the breakpoint is hit
**No Optimization**

- **gcc -O0**
  - All stack frames are present

```
08046b78:  c+3(1, 0, 0, fefa3000)
08046b98:  b+0x11(1, 80509e4, feffb350, 8)
08046bb8:  a+0x11(1, fee9431c, 29, fefab85c)
08046bec:  main+0x27(1, 8046c10, 8046c18)
08046c04:  _start+0x80(1, 8046d60, 0, ...)
```
Better Optimization

- **gcc -O1**
  - `c()` is leaf-optimized
    - `c()` is not creating its own stack frame
    - `c()` is using `b()`'s stack frame
      - Thus `b()` is not shown in the stack trace

```
08046b78:  c(1, 80509e8, feffb350, 8)
08046bb8:  a+0xe(1, fee9431c, 29, fefab85c)
08046bec:  main+0x14(1, 8046c10, 8046c18)
08046c04:  _start+0x80(1, 8046d60, 0, ...)
```
Even Better Optimization

- `gcc -O2`
  - `a()` and `b()` is tail-call-optimized
    - `a()` and `b()` recycle the caller's stack frame
    - Thus `a()`, `b()` and `main()` are not shown in the trace
  - `c()` is leaf-optimized (as previously)

```
08046b78:  c(1, 8046c10, 8046c18)
08046c04:  _start+0x80(1, 8046d60, 0, ...)
```
Best Optimization

- gcc -O3
  - Function inlining on a(), b() and c()
    - Thus a(), b(), c() not even called by main()
    - Our breakpoint is not even hit
  - a() and b() is tail-call-optimized (as previously)
  - c() is leaf-optimized (as previously)
## Morale of the Example

- **Compiler optimizations produce better (faster) code**

- **Optimized code is harder to debug**
  - Inlined functions
  - Missing stack frames
  - Untraceable argument values

- **Optimized code is harder to understand**
  - Relation between source code and machine code is not straightforward
Special Stack Frames

- **Trap frames**
  - Created by interrupt or exception (trap) handlers
    - Contain values of all registers in the time the trap occurred
    - Also saved on the stack
  - Usually not visible in a core dump (user space)
  - Can be seen in a crash dump (when code is in kernel)
  - If time permits, more details later in the course
ABI Revisited

- Two parts of every ABI
  - Defined by architecture/platform (hard-wired)
  - Defined by the run-time environment

- What is specified (among others)
  - Set of volatile and non-volatile GPRs
  - Calling convention
    - Who creates and destroys stack frames
    - The way function arguments and return values are passed
  - Stack layout
ABI Revisited (2)

- UNIX System V Application Binary Interface
  - Intel386 Architecture Processor Supplement
  - AMD64 Architecture Processor Supplement
  - SPARC Compliance Definition

- Windows ABI
  - stdcall,fastcall, etc.
  - x64 Software Conventions
Compiler Toolchain

- `.c`
- `.h`

preprocessor \rightarrow .i \rightarrow compiler \rightarrow .s \rightarrow assembler

```
cc -c -o output.o input.c
as -o output.o input.s
```
Linking

ld -T link.ld -o output.bin input0.o input1.o
input0.c

```c
void global_fnc01() { }
void global_fnc02() { }

int global_int;
void *global_ptr;

int another_symbol __attribute__((section("another_section")));
```

input0.o

```assembly
.text
  global_fnc01
  global_fnc02
.bss
  global_int
  global_ptr
  another_section
  another_symbol
```
Linking (3)

link.ld

SECTIONS {
  .output 0x80000000 : {
    *(.text)
    *(.bss)
    *(another_section)
    _output_end = .;
  }
}

output.bin

.output (displacement: 0x80000000)
  global_fnc01
  global_fnc02
  global_int
  global_ptr
  another_symbol
  _output_end
Useful Tools

- objdump
  - Display various information about binary files
    - `-x`
      - Display all headers
    - `-d`
      - Disassemble executable sections
    - `-D`
      - Disassemble all sections
    - `-S`
      - Disassemble with source file intermixed
      - Debugging information is needed (gcc -g)