Lecture 2: Bits, Bytes and Integers – Part 1

1 Byte = 8 bits

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

C Data Type	Typical 32-bit	Typical 64-bit	x86-64
char	1	1	1
short	2	2	2
int	4	4	4
long	4	8	8
float	4	4	4
double	8	8	8
pointer	4	8	8

Encoding Integers

Unsigned: $B2U(x) = \sum_{i=0}^{w-1} x_i \cdot 2^i$

Two's Complement: $B2T(x) = -x_{w-1} \cdot 2^{w-1} + \sum_{i=0}^{w-2} x_i \cdot 2^i$

Numeric Ranges

Unsigned Values: $UMin = 0$, $UMax = 2^w - 1$

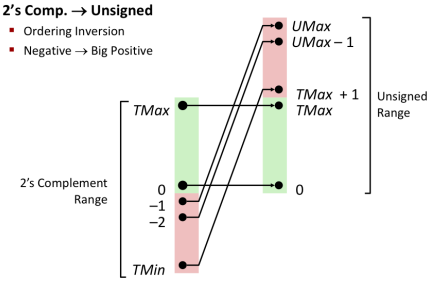
Two's Complement Values: $TMin = -2^{w-1}$, $TMax = 2^{w-1} - 1$, $-1 = 11\cdots11$

$|TMin| = TMax + 1$

$UMax = 2 * TMax + 1$

Conversion Visualized

- 2's Comp. → Unsigned
  - Ordering Inversion
  - Negative → Big Positive



- If there is a mix of unsigned and signed in single expression, signed values implicitly cast to unsigned

Sign Extension

- Given w-bit signed integer x
- Convert it to (w+k) bit integer with same value

⇒ Make k copies of sign bit

Truncation

- Given k+w bit signed or unsigned integer x
- Convert it to w-bit integer x' (with small value for "small enough" x)

⇒ Drop top k bits

Lecture 3: Bits, Bytes and Integers – Part 2

Unsigned Addition: $s = UAdd_w(u,v)$ (Discard Carry) $= (u+v) \bmod 2^w$

Two's Complement Addition:

if sum $\geq 2^{w-1}$: Becomes Negative At most once

if sum $< -2^{w-1}$: Becomes Positive At most once

Power-of-2 Multiply with Shift

$u << k$ gives $u * 2^k$

Unsigned Power-of-2 Divide with Shift

$u >> k$ gives $\lfloor u/2^k \rfloor$ (logical shift)

Signed Power-of-2 Divide with Shift

$x >> k$ gives $\lfloor x/2^k \rfloor$ (arithmetic shift)

$(x + (1<<k) - 1) >> k \Rightarrow \lfloor (x + 2^k - 1)/2^k \rfloor$

$\Rightarrow \lceil x/2^k \rceil$

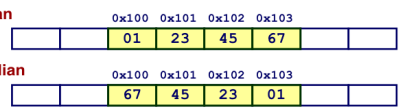
Complement & Increment: $\sim x + 1 == -x$

Size_t: unsigned value with length = word size

Byte Ordering

- Big Endian: Sun (Oracle SPARC), PPC Mac, *Internet*
  - Least significant byte has highest address
- Little Endian: *x86*, ARM processors running Android, iOS, and Linux
  - Least significant byte has lowest address

Example: 4-byte value: 0x01234567



Lecture 4: Floating Point

Floating Point Representation

- **Numerical Form:** $(-1)^s M\ 2^E$

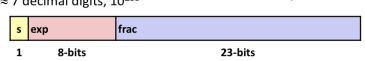
  Example: $15213_{10} = (-1)^0 \times 1.1101101101101_2 \times 2^{13}$

  - **Sign bit** *s* determines whether number is negative or positive
  - **Significand** *M* normally a fractional value in range [1.0,2.0).
  - **Exponent** *E* weights value by power of two

- **Encoding**
  - MSB s is sign bit *s*
  - **exp** field encodes *E* (but is not equal to E)
  - **frac** field encodes *M* (but is not equal to M)

- **Single precision: 32 bits** ≈ 7 decimal digits, $10^{\pm 38}$

  Precision options



- **Double precision: 64 bits** ≈ 16 decimal digits, $10^{\pm 308}$

Normalized Value

$exp \neq 00\cdots0$ && $exp \neq 11\cdots1$

$E = Exp - Bias$

$Bias = 2^{k-1} - 1$ { single precision: 127; Double precision: 1023

$M = 1.xxx\cdots x$ (frac field)

Denormalized Values

$exp = 00\cdots0$

$E = 1 - Bias$

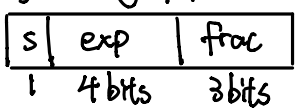
$M = 0.xx\cdots x$

Special Values

$exp = 11\cdots1$

$frac$ { $= 00\cdots0 \Rightarrow \infty$; $\neq 00\cdots0 \Rightarrow NaN$

Tiny Floating Point Example



Dynamic Range (Positive Only)

$v = (-1)^s M\ 2^E$

n: E = Exp – Bias

d: E = 1 – Bias

Bias = 7

	s	exp	frac	E	Value	
	0	0000	000	-6	0	
	0	0000	001	-6	1/8*1/64 = 1/512	closest to zero
Denormalized numbers	0	0000	010	-6	2/8*1/64 = 2/512	$(-1)^0(0+1/4)*2^{-6}$
	…					
	0	0000	110	-6	6/8*1/64 = 6/512	
	0	0000	111	-6	7/8*1/64 = 7/512	largest denorm
	0	0001	000	-6	8/8*1/64 = 8/512	smallest norm
	0	0001	001	-6	9/8*1/64 = 9/512	$(-1)^0(1+1/8)*2^{-6}$
	…					
	0	0110	110	-1	14/8*1/2 = 14/16	
	0	0110	111	-1	15/8*1/2 = 15/16	closest to 1 below
Normalized numbers	0	0111	000	0	8/8*1 = 1	
	0	0111	001	0	9/8*1 = 9/8	closest to 1 above
	0	0111	010	0	10/8*1 = 10/8	
	…					
	0	1110	110	7	14/8*128 = 224	
	0	1110	111	7	15/8*128 = 240	largest norm
	0	1111	000	n/a	inf	

Rounding

1.BBGRXXX

Guard bit (LSB of result), Round bit, Sticky bit

Round = 1, Sticky ≠ 0 → > 0.5

Guard = 1, Round = 1, Sticky = 0 → Round to even

- `x == (int)(float) x` ✗
- `x == (int)(double) x` ✓
- `f == (float)(double) f` ✓
- `d == (double)(float) d` ✗
- `f == -(-f);` ✓
- `2/3 == 2/3.0` ✗
- `d < 0.0 ⇒ ((d*2) < 0.0)` ✓
- `d > f ⇒ -f > -d` ✓
- `d * d >= 0.0` ✓
- `(d+f)-d == f` ✗

Lecture 5: Machine-Level Programming I: Basic

x86-64 Integer Registers: %rax, %rbx, %rcx, %rdx, %rsi, %rdi, %rsp, %rbp, %r8, %r9, ⋯, %r15

D(Rb,Ri,S) ⇒ Mem[Reg[Rb] + S*Reg[Ri] + D]

Instructions:

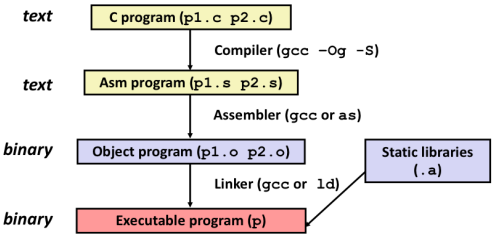
`movq Src, Dst`

`leaq Src, Dst`

(`leaq (%rdi,%rdi,2), %rax` ⇒ rax = 2*rdi + rdi)

addq	Src,Dest	Dest = Dest + Src	incq	Dest	Dest = Dest + 1
subq	Src,Dest	Dest = Dest − Src	decq	Dest	Dest = Dest − 1
imulq	Src,Dest	Dest = Dest * Src	negq	Dest	Dest = − Dest
salq	Src,Dest	Dest = Dest << Src	notq	Dest	Dest = ~Dest
sarq	Src,Dest	Dest = Dest >> Src			
shrq	Src,Dest	Dest = Dest >> Src			
xorq	Src,Dest	Dest = Dest ^ Src			
andq	Src,Dest	Dest = Dest & Src			
orq	Src,Dest	Dest = Dest | Src			

Turning C into Object Code



Lecture 6: Machine-Level Programming II: Control

%rsp: Current Stack Top

%rip: Instruction pointer

Condition codes: CF, ZF, SF, OF

- CF: Carry Flag (for unsigned)
- SF: Sign Flag (for signed)
- ZF: Zero Flag
- OF: Overflow Flag (for signed)

Cmpq Src2, Src1:
cmpq b, a like computing a-b without setting destination

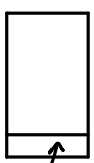
testq Src2, Src1:
testq b, a like computing a&b without setting destination

SetX Dest:
Set low-order byte of destination Dest to 0 or 1 based on combinations of condition codes.

jX Instructions:
Jump to different part of code depending on condition codes

Lecture 7: Machine-Level Programming III

x86-64 Stack



Stack "Bottom"

↑ increasing addresses

↓ Stack grows down

Stack "Top"

%rsp: Contains lowest stack address

push Src:
1. Fetch operand at Src
2. Decrement %rsp by 8
3. Write operand at address given by %rsp

popq Dest:
1. Read value at address given by %rsp
2. Increment %rsp by 8
3. Store value at Dest (usually a register)

(The memory doesn't change, only %rsp)

Procedure call: call label
1. Push return address on stack
2. Jump to label

Procedure return: ret
1. Pop address from stack
2. Jump to address

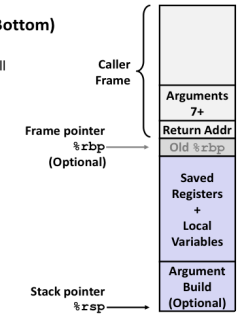
Passing data

First 6 argument: %rdi, %rsi, %rdx, %rcx, %r8, %r9

Return value: %rax

x86-64/Linux Stack Frame

- **Current Stack Frame ("Top" to Bottom)**
  - "Argument build:" Parameters for function about to call
  - Local variables If can't keep in registers
  - Saved register context
  - Old frame pointer (optional)
- **Caller Stack Frame**
  - Return address
    - Pushed by `call` instruction
  - Arguments for this call



Caller-saved: %r10, %r11

Callee-saved: %rbx, %r12, %r13, %r14

Lecture 8: Machine-Level Programming IV: Data

T A[L];
- Array of data type T and length L
- Contiguously allocated region of L * sizeof(T)

int (*A3)[3]: A3 is a pointer to a array with 3 integers (A3 → int[3])

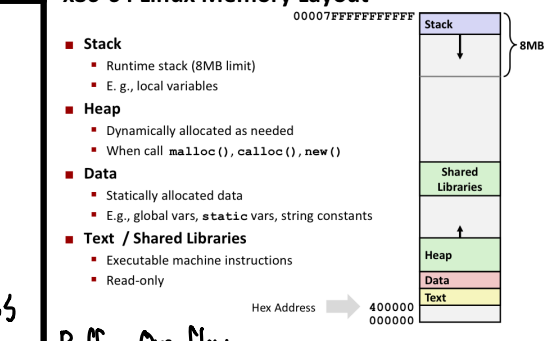
T A[R][C];
- A[i] address: A + i*(C*sizeof(T))
- A[i][j] address: A + i*(c*k) + j*k = A + (i*C + j)*K

Structure Alignment:
1. Primitive data type requires K bytes
2. Address must be multiple of K

Unions: 1. Allocated according to largest element
2. Can only use one field at a time

Lecture 9: Machine Level Programming: Advanced

x86-64 Linux Memory Layout



- **Stack**
  - Runtime stack (8MB limit)
  - E. g., local variables
- **Heap**
  - Dynamically allocated as needed
  - When call `malloc(), calloc(), new()`
- **Data**
  - Statically allocated data
  - E.g., global vars, `static` vars, string constants
- **Text / Shared Libraries**
  - Executable machine instructions
  - Read-only

Buffer Overflow

1. Stack Smashing Attacks: Overwrite normal return address with address of some other code
2. Code Injection Attacks: Input string contains byte representation of executable code; Overwrite return address A with address of buffer B

Protection:
1. Avoid Overflow Vulnerability in code
2. System-Level Protection: Random stack offsets; Nonexecutable code segments
3. Stack Canaries: Place special value on stack just beyond buffer

Return-Oriented Programming Attacks

Construct program from gadgets
1. Sequence of instructions ending in ret
2. Code positions fixed from run to run (0xc3)
3. Code is executable

Lecture 10: Code Optimization

16 * X → X << 4

Move call to strlen outside of loop

CPE = cycles per OP

Loop Unrolling

Branch Prediction Numbers
- Backwards branches are often loops so predict taken
- Forwards branches are often if so predict not taken

Lecture 11: The Memory Hierarchy

RAM { SRAM: fast, expensive
DRAM: slow, cheap

Disk: Capacity = (# bytes/sector) x (avg. # sectors/track) x (# tracks/surface) x (# surfaces/platter) x (# platters/disk)

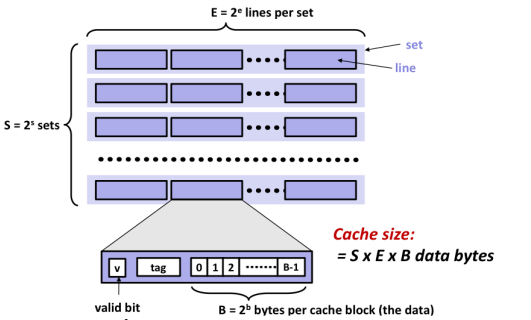
Disk Access Time
1. Seek time ($T_{avg\ seek}$)
2. Rotational latency ($T_{avg\ rotation}$)
   $T_{avg\ rotation} = \frac{1}{2} \times \frac{1}{RPMs} \times \frac{60\ sec}{1\ min}$
3. Transfer time ($T_{avg\ transfer}$)
   $T_{avg\ transfer} = \frac{1}{RPMs} \times \frac{1}{(avg\ \#\ sectors/track)} \times \frac{60\ sec}{1\ min}$

Locality { Temporal locality
Spatial locality

3 Types of Cache Misses
1. Cold (compulsory) miss
2. Capacity miss
3. Conflict miss

Lecture 12: Cache Memories

General Cache Organization (S, E, B)



Address of word: t bits | s bits | b bits

t bits: tag; s bits: set index; b bits: block offset

Direct Mapped Cache: E=1

E-way Set Associative Cache

write-hit: { Write-through
Write-back

write-miss: { write-allocate
no-write-allocate

Typical: write-through + no-write-allocate
write-back + write-allocate

Lecture 13: Linking

What do linkers do?

1. Step 1: Symbol resolution
   - associates each symbol reference with exact one symbol definition
2. Step 2: Relocation
   - merges separate code and data sections into single

sections.
- Relocates symbols from their relative locations in the .o files to their final absolute memory locations in the executable
- Updates all references to these symbols to reflect their new positions.

ELF Object File Format

- **Elf header**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc.
- **Segment header table**
  - Page size, virtual addresses memory segments (sections), segment sizes.
- **`.text` section**
  - Code
- **`.rodata` section**
  - Read only data: jump tables, string constants, ...
- **`.data` section**
  - Initialized global variables
- **`.bss` section**
  - Uninitialized global variables
  - "Block Started by Symbol"
  - "Better Save Space"
  - Has section header but occupies no space
- **`.symtab` section**
  - Symbol table
  - Procedure and static variable names
  - Section names and locations
- **`.rel.text` section**
  - Relocation info for `.text` section
  - Addresses of instructions that will need to be modified in the executable
  - Instructions for modifying.
- **`.rel.data` section**
  - Relocation info for `.data` section
  - Addresses of pointer data that will need to be modified in the merged executable
- **`.debug` section**
  - Info for symbolic debugging (`gcc -g`)
- **Section header table**
  - Offsets and sizes of each section

ELF header
Segment header table (required for executables)
`.text` section
`.rodata` section
`.data` section
`.bss` section
`.symtab` section
`.rel.txt` section
`.rel.data` section
`.debug` section
Section header table

ELF header
Segment header table (required for executables)
`.text` section
`.rodata` section
`.data` section
`.bss` section
`.symtab` section
`.rel.txt` section
`.rel.data` section
`.debug` section
Section header table

Linker Symbols
- Global symbols: Symbols defined by module m that can be referenced by other modules.
- External symbols: Global symbols that are referenced by module m but defined by some other module
- Local symbols: Symbols that are defined and referenced exclusively by module m.

Static
- Symbol only visible in enclosing scope
- Stored in either .bss or .data

Program symbols are either strong or weak
- Strong: procedures and initialized globals
- Weak: uninitialized globals
- Very weak: uninitialized globals declared with extern

Linker's Symbol Rules
- Rule 1: Multiple strong symbols are not allowed
- Rule 2: Given a strong symbol and multiple weak symbols, choose the strong
- Rule 3: If there are multiple weak symbols, pick an arbitrary one
- Rule 4: Never pick a "very weak" symbol

Lecture 14: Exceptional Control Flow: Exceptions and Processes

Exception: An exception is a transfer of control to the OS kernel in response to some event

ECF ← Asynchronous — Interrupts (I/O...)
Synchronous ← Traps (intentional), Faults (unintentional), Aborts (unintentional)

Traps: System call
Faults: Page fault
Aborts: segmentation fault

Process: an instance of a running program
Logical control flow & private address space

Processes: Running, Stopped, Terminated

exit: Called once but never returns
fork: Called once but return twice
(return 0 to child, child's PID to parent)

Reaping Child Processes:
When process terminated, it still consume system resources

wait: Parent reaps a child by calling "wait"

execve: Loading and Running Programs
- Overwrites code, data and stack
- Retains PID, open files and signal context
- Called once and never returns

Lecture 15: Exceptional Control Flow: Signals and Nonlocal Jumps

Shell: A shell is an application program that runs programs on behalf of the user

Signals: A signal is a small message that notifies a process that an event of some type has occured in the system

Kernel sends a signal to a destination process by updating some state in the context of the destination process.

Destination process receives a signal:
① Ignore the signal
② Terminate the process
③ Catch the signal by executing a user-level function called signal handler

pending: A signal is sent but not yet received
block: A process blocks the receipt of certain signals

- Kernel maintains `pending` and `blocked` bit vectors in the context of each process
  - `pending`: represents the set of pending signals
    - Kernel sets bit k in `pending` when a signal of type k is delivered
    - Kernel clears bit k in `pending` when a signal of type k is received
  - `blocked`: represents the set of blocked signals
    - Can be set and cleared by using the `sigprocmask` function
    - Also referred to as the *signal mask*.

Each signal type has a predefined default action

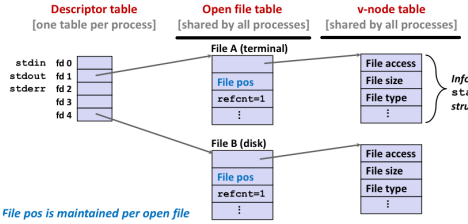
Lecture 16: System-Level I/O

A Linux file is a sequence of m bytes

open: returns a small identifying integer file descriptor.
0: standard input (stdin)
1: standard output (stdout)
2: standard error (stderr)

File Metadata: data about data

How the Unix Kernel Represents Open Files



I/O Redirection: dup2(4,1)
cause fd=1 (stdout) to refer to disk file pointed at by fd=4

Lecture 17: Virtual Memory: Concepts

CPU → Virtual Address (VA) → MMU → Physical Address (PA)

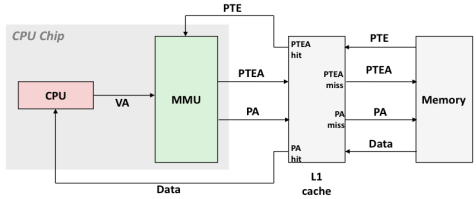
Page Table: A page table is an array of page table entries (PTEs) that maps virtual pages to physical pages

Page Hit vs Page Fault

working set: at any point of time, programs tend to access a set of active virtual pages.

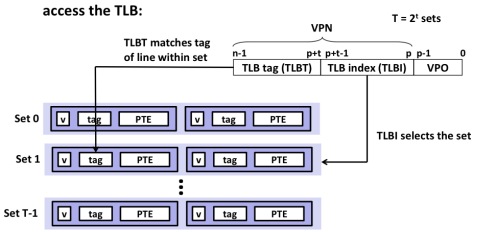
Each process has its own virtual address space

Address Translation Symbols: $N=2^n$ (VA), $M=2^m$ (PA), $P=2^p$ (page size), VPO: virtual page offset, VPN: virtual page number, PPO, PPN



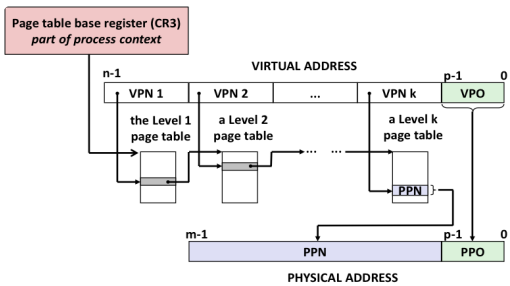
TLB: Translation Lookaside Buffer
- Maps virtual page numbers to physical page numbers
- Contains complete page table entries for small number of pages

- MMU uses the VPN portion of the virtual address to access the TLB:



Lecture 18: Virtual Memory: Systems

K-Level Page Table

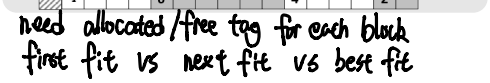


Lecture 19: Dynamic Memory Allocation: Basic Concepts

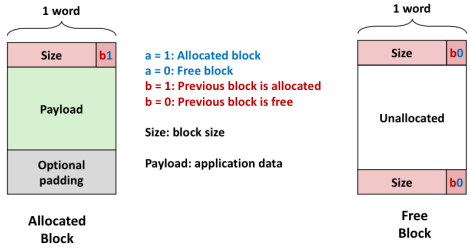
- ***Def:* Aggregate payload P_k**
  - `malloc(p)` results in a block with a ***payload*** of p bytes
  - After request R_k has completed, the ***aggregate payload*** P_k is the sum of currently allocated payloads
- ***Def:* Current heap size H_k**
  - Assume H_k is monotonically nondecreasing
    - i.e., heap only grows when allocator uses `sbrk`
- ***Def:* Peak memory utilization after k+1 requests**
  - $U_k = (max_{i \le k} P_i) \ / \ H_k$

internal fragmentation: payload < block size
external fragmentation: there is enough aggregate heap memory, but no single free block is large enough

Method 1: *Implicit list* using length—links all blocks

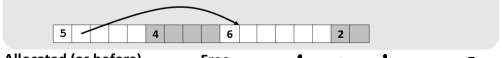


need allocated/free tag for each block
first fit vs next fit vs best fit

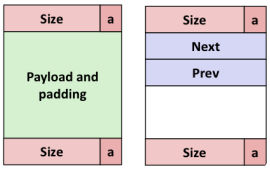


Lecture 20: Dynamic Memory Allocation: Advanced Concepts

Method 2: *Explicit free list* among the free blocks using pointers



Allocated (as before) / Free



Maintain list(s) of free blocks, not all blocks

Segregated List (seglist) Allocators: Each size class of blocks has its own free list

Lecture 21: Network Programming: Part I

IP addresses: 32-bit IP addresses are stored in an "IP address struct".

- IP addresses are always stored in memory in network byte order (big-endian byte order)

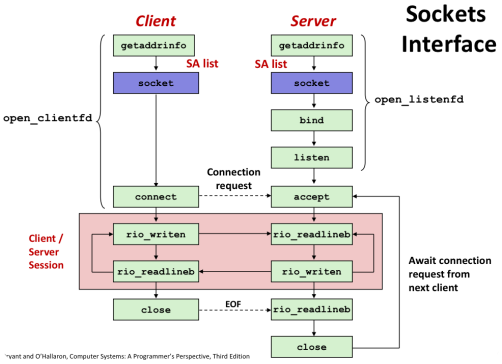
Clients and servers communicate by sending streams of bytes over connections.

A socket is an endpoint of a connection

- Socket address is an IP address : port pair

A port is a 16-bit integer that identifies a process

Lecture 22: Network Programming: Part II



HTTP Requests

Request line: <method> <uri> <version>

- A URL is a type of URI

Request headers: <header name>: <header data>

HTTP Response

Response line: <version> <status code> <status msg>

Response headers: <header name>: <header data>

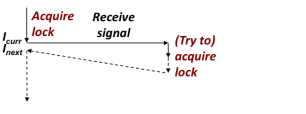
- Content-Type
- Content-Length

Lecture 23: Concurrent Programming

Deadlock:

```
void catch_child(int signo) {
   printf("Child exited!\n"); // this call may reenter printf/puts! BAD! DEADLOCK!
   while (waitpid(-1, NULL, WNOHANG) > 0) continue; // reap all children
}
```

- **Printf code:**
  - Acquire lock
  - Do something
  - Release lock



Data Race:

- two or more threads in a **single process** access the same memory location concurrently, and
- at least one of the accesses is for writing, and
- the threads are not using any exclusive locks to control their accesses to that memory.

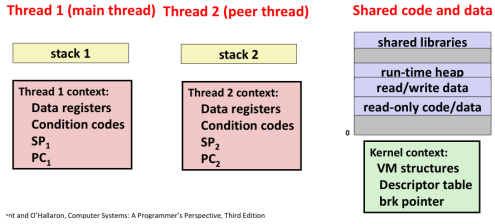
Starvation

Process = process context + code, data, and stack

Process: thread + code, data, and kernel context

A Process With Multiple Threads

- **Multiple threads can be associated with a process**
  - Each thread has its own logical control flow
  - Each thread shares the same code, data, and kernel context
  - Each thread has its own stack for local variables
    - but not protected from other threads
  - Each thread has its own thread id (TID)



Lecture 24: Synchronization: Basic

- **Global variables**
  - *Def:* Variable declared outside of a function
  - **Virtual memory contains exactly one instance of any global variable**
- **Local variables**
  - *Def:* Variable declared inside function without `static` attribute
  - **Each thread stack contains one instance of each local variable**
- **Local static variables**
  - *Def:* Variable declared inside function with the `static` attribute
  - **Virtual memory contains exactly one instance of any local static variable.**

We must synchronize the execution of the threads so that they can never have an unsafe trajectory

Semaphore: non-negative global integer synchronization variable

P(s): If s is nonzero, then decrement s by 1 and return immediately

V(s): Increments s by 1

Lecture 25: Synchronization: Advanced

Producer-Consumer on 1-element Buffer

Initially: `empty==1, full==0`

Producer Thread

```
void *producer(void *arg) {
  int i, item;

  for (i=0; i<NITERS; i++) {
    /* Produce item */
    item = i;
    printf("produced %d\n",
           item);

    /* Write item to buf */
    P(&shared.empty);
    shared.buf = item;
    V(&shared.full);
  }
  return NULL;
}
```

Consumer Thread

```
void *consumer(void *arg) {
  int i, item;

  for (i=0; i<NITERS; i++) {
    /* Read item from buf */
    P(&shared.full);
    item = shared.buf;
    V(&shared.empty);

    /* Consume item */
    printf("consumed %d\n", item);
  }
  return NULL;
}
```

Variants of Readers-Writers

- ***First readers-writers problem*** **(favors readers)**
  - No reader should be kept waiting unless a writer has already been granted permission to use the object.
  - A reader that arrives after a waiting writer gets priority over the writer.
- ***Second readers-writers problem*** **(favors writers)**
  - Once a writer is ready to write, it performs its write as soon as possible
  - A reader that arrives after a writer must wait, even if the writer is also waiting.

Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
  }
}
```

Writers:

```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

Second Version

```
// Pseudo code for the second version of reader-writer problem:
int readcount, writecount; (initial value = 0)
semaphore mutex_1, mutex_2, mutex_3, w, r ; (initial value = 1)
```

READER:

```
While (true){
  wait(mutex_3);
    wait(r);
      wait(mutex_1);
        readcount := readcount + 1;
        if readcount = 1 then wait(w);
      signal(mutex_1);
    signal(r);
  signal(mutex_3);

//  reading is performed

  wait(mutex_1);
    readcount := readcount - 1;
    if readcount = 0 then signal(w);
  signal(mutex_1);
}
```

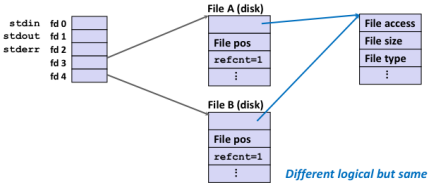
WRITER:

```
while(true) {
  wait(mutex_2);
    writecount := writecount + 1;
    if writecount = 1 then wait(r);
  signal(mutex_2);

  wait(w);
     // writing is performed
  signal(w);

  wait(mutex_2);
    writecount := writecount - 1;
    if writecount = 0 then signal(r);
  signal(mutex_2);
}
```

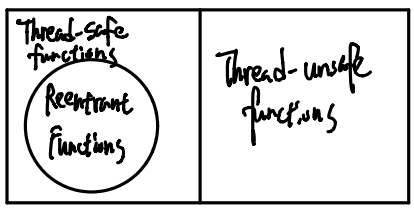
File Sharing



Different logical but same physical file

Many readers can hold the same rwlock at the same time.

Reentrant Functions: A function is reentrant iff it accesses no shared variables when called by multiple threads.



waitpid: return exactly once

A new connection arrives on a listening socket will not generate a signal