C declaration	Intel data type	Assembly-code suffix	Size (bytes)
`char`	Byte	`b`	1
`short`	Word	`w`	2
`int`	Double word	`l`	4
`long`	Quad word	`q`	8
`char *`	Quad word	`q`	8
`float`	Single precision	`s`	4
`double`	Double precision	`l`	8

63	31	15	7 0	
%rax	%eax	%ax	%al	Return value
%rbx	%ebx	%bx	%bl	Callee saved
%rcx	%ecx	%cx	%cl	4th argument
%rdx	%edx	%dx	%dl	3rd argument
%rsi	%esi	%si	%sil	2nd argument
%rdi	%edi	%di	%dil	1st argument
%rbp	%ebp	%bp	%bpl	Callee saved
%rsp	%esp	%sp	%spl	Stack pointer
%r8	%r8d	%r8w	%r8b	5th argument
%r9	%r9d	%r9w	%r9b	6th argument
%r10	%r10d	%r10w	%r10b	Caller saved
%r11	%r11d	%r11w	%r11b	Caller saved
%r12	%r12d	%r12w	%r12b	Callee saved
%r13	%r13d	%r13w	%r13b	Callee saved
%r14	%r14d	%r14w	%r14b	Callee saved
%r15	%r15d	%r15w	%r15b	Callee saved

Type	Form	Operand value	Name
Immediate	$\$Imm$	Imm	Immediate
Register	r_a	$R[r_a]$	Register
Memory	Imm	$M[Imm]$	Absolute
Memory	(r_a)	$M[R[r_a]]$	Indirect
Memory	$Imm(r_b)$	$M[Imm + R[r_b]]$	Base + displacement
Memory	(r_b, r_i)	$M[R[r_b] + R[r_i]]$	Indexed
Memory	$Imm(r_b, r_i)$	$M[Imm + R[r_b] + R[r_i]]$	Indexed
Memory	$(, r_i, s)$	$M[R[r_i] \cdot s]$	Scaled indexed
Memory	$Imm(, r_i, s)$	$M[Imm + R[r_i] \cdot s]$	Scaled indexed
Memory	(r_b, r_i, s)	$M[R[r_b] + R[r_i] \cdot s]$	Scaled indexed
Memory	$Imm(r_b, r_i, s)$	$M[Imm + R[r_b] + R[r_i] \cdot s]$	Scaled indexed

```
movl $0x4050,%eax       Immediate--Register, 4 bytes
movw %bp,%sp            Register--Register,  2 bytes
movb (%rdi,%rcx),%al    Memory--Register,    1 byte
movb $-17,(%esp)        Immediate--Memory,   1 byte
movq %rax,-12(%rbp)     Register--Memory,    8 bytes
```

Instruction		Effect	Description
`leaq`	S, D	$D \leftarrow \&S$	Load effective address
INC	D	$D \leftarrow D+1$	Increment
DEC	D	$D \leftarrow D-1$	Decrement
NEG	D	$D \leftarrow -D$	Negate
NOT	D	$D \leftarrow \sim D$	Complement
ADD	S, D	$D \leftarrow D + S$	Add
SUB	S, D	$D \leftarrow D - S$	Subtract
IMUL	S, D	$D \leftarrow D * S$	Multiply
XOR	S, D	$D \leftarrow D \,\hat{}\, S$	Exclusive-or
OR	S, D	$D \leftarrow D \mid S$	Or
AND	S, D	$D \leftarrow D \,\&\, S$	And
SAL	k, D	$D \leftarrow D << k$	Left shift
SHL	k, D	$D \leftarrow D << k$	Left shift (same as SAL)
SAR	k, D	$D \leftarrow D >>_A k$	Arithmetic right shift
SHR	k, D	$D \leftarrow D >>_L k$	Logical right shift

CF	`(unsigned) t < (unsigned) a`	Unsigned overflow
ZF	`(t == 0)`	Zero
SF	`(t < 0)`	Negative
OF	`(a < 0 == b < 0) && (t < 0 != a < 0)`	Signed overflow

CMP S1, S2 (S2 – S1) TST S1, S2 (S1 & S2)

Instruction		Synonym	Effect	Set condition
`sete`	D	`setz`	$D \leftarrow$ ZF	Equal / zero
`setne`	D	`setnz`	$D \leftarrow$ ~ ZF	Not equal / not zero
`sets`	D		$D \leftarrow$ SF	Negative
`setns`	D		$D \leftarrow$ ~ SF	Nonnegative
`setg`	D	`setnle`	$D \leftarrow$ ~ (SF ^ OF) & ~ZF	Greater (signed >)
`setge`	D	`setnl`	$D \leftarrow$ ~ (SF ^ OF)	Greater or equal (signed >=)
`setl`	D	`setnge`	$D \leftarrow$ SF ^ OF	Less (signed <)
`setle`	D	`setng`	$D \leftarrow$ (SF ^ OF) | ZF	Less or equal (signed <=)
`seta`	D	`setnbe`	$D \leftarrow$ ~ CF & ~ZF	Above (unsigned >)
`setae`	D	`setnb`	$D \leftarrow$ ~ CF	Above or equal (unsigned >=)
`setb`	D	`setnae`	$D \leftarrow$ CF	Below (unsigned <)
`setbe`	D	`setna`	$D \leftarrow$ CF | ZF	Below or equal (unsigned <=)

`jmp` *Label*	1	Direct jump
`jmp` **Operand*	1	Indirect jump

Callee Saved – Responsibility of function called to save the value before returning to function that called it. 1-6th arguments are Caller Saved

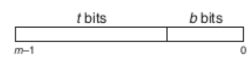
A struct within a struct gets aligned by largest value of struct

Parameter	Description
Fundamental parameters	
$S = 2^s$	Number of sets
E	Number of lines per set
$B = 2^b$	Block size (bytes)
$m = \log_2(M)$	Number of physical (main memory) address bits
Derived quantities	
$M = 2^m$	Maximum number of unique memory addresses
$s = \log_2(S)$	Number of *set index bits*
$b = \log_2(B)$	Number of *block offset bits*
$t = m - (s + b)$	Number of *tag bits*
$C = B \times E \times S$	Cache size (bytes), not including overhead such as

Set associative cache ($1 < E < C/B$). In a set associative cache, each set contains more than one line. This particular example shows a two-way set associative cache. < E=2

Figure 6.35 **Fully associative cache** ($E = C/B$). In a fully associative cache, a single set contains all of the lines.

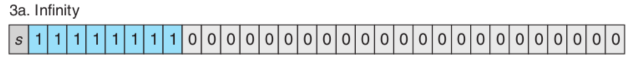
The entire cache is one set, so by default set 0 is always selected.



1. Normalized

2. Denormalized

3a. Infinity



3b. NaN

For normalized numbers:
M = 1.xxxx
E = exp - bias

For denormalized numbers:
M = 0.xxxx
E = 1 - bias

Bias = 2^(k-1)-1 V = (-1)^s*M*2^E

Floating Point: Rounding

1.BGRXXX

In the below examples, imagine the underlined part as a fraction.

- Guard Bit: the least significant bit of the resulting number
- Round Bit: the first bit removed from rounding
- Sticky Bits: all bits after the round bit, OR'd together

Examples of rounding cases, including rounding to nearest even number

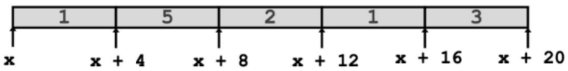
- 1.10|11: More than ½, round up: 1.11
- 1.10|10: Equal to ½, round down *to even*: 1.10
- 1.01|01: Less than ½, round down: 1.01
- 1.01|10: Equal to ½, round up *to even*: 1.10
- 1.01|00: Equal to 0, do nothing: 1.01
- 1.00 00: Equal to 0, do nothing: 1.00

All other cases involve either rounding up or down - *try them*!

Bonus Coverage: Arrays

Good toy examples (for your cheatsheet and/or big brain):

`int val[5];`



- A can be used as the pointer to the first array element: A[0]

	Type	Value
val	int *	x
val[2]	int	2
*(val + 2)	int	2
&val[2]	int *	x + 8
val + 2	int *	x + 8
val + i	int *	x + (4 * i)

Accessing methods:
- val[index]
- *(val + index)

Addressing methods:
- &val[index]
- val + index

Bonus Coverage: Arrays

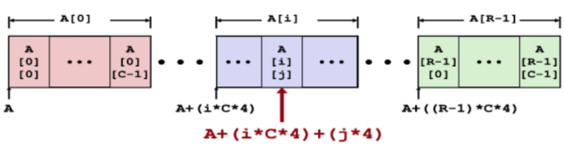
Nested indexing rules (for your cheatsheet and/or big brain):

A[i][j] is element of type *T*, which requires *K* bytes

Address **A + i * (C * K) + j * K**

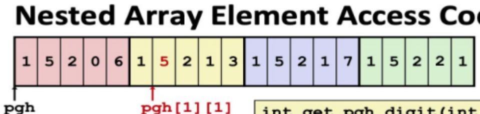
= A + (i * C + j) * K

`int A[R][C];`



Bonus Coverage: Arrays

Nested Array Element Access Code




```
int get_pgh_digit(int index, int dig)
{
  return pgh[index][dig];
}
```

```
leaq  (%rdi,%rdi,4), %rax     # 5*index
addl  %rax, %rsi              # 5*index+dig
movl  pgh(,%rsi,4), %eax      # M[pgh + 4*(5*index+dig)]
```

- **Array Elements**
  - **pgh[index][dig]** is **int**
  - Address: **pgh + 20*index + 4*dig**
    = pgh + 4*(5*index + dig)

```
char c = 0xF0;
if(0xF0 == c){
    //Never Enters unless GCCd
    //c == 0xFFFFFFF0;
}
```

```
printf(%x);
//Does not include 0x
printf("0x%.8x \n")
//Prints in Little Endian
printf("0x%hx \n")
//Prints in Little Endian
```

```
Floats are four bytes!
Addresses on the stack are in order
All other data types on stack little endian (pointers too)
! - > turns thing into signed ints
Size then sinage
```

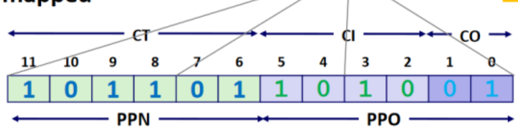
Struct
int i;
float f;

i =0x6942
f =0x 4200

42, 69, 00, 00,
00, 42, 00, 00,

- **16 lines, 4-byte cache line size**
- **Physically addressed**
- **Direct mapped**

V[0b00001101101001] = V[0x369]
P[0b101101101001] = P[0xB69] = 0x15



$$T2U_w(x) = \begin{cases} x + 2^w, & x < 0 \\ x, & x \geq 0 \end{cases}$$

$$B2U_w(T2B_w(x)) = T2U_w(x) = x + x_{w-1}2^w$$

$$U2T_w(u) = \begin{cases} u, & u \leq TMax_w \\ u - 2^w, & u > TMax_w \end{cases}$$

$$U2T_w(u) = -u_{w-1}2^w + u$$

$$x *^u_w y = (x \cdot y) \bmod 2^w$$

$$x *^t_w y = U2T_w((x \cdot y) \bmod 2^w)$$

i[0]= 0x69

[i[1], i[0]] ← rsp

read R to L

[~~~, 0x000069]

[ ]

char [rsp] = 69

char [rsp+1] = 00

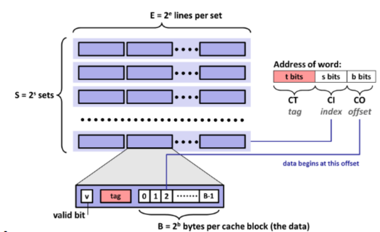
PRINCIPLE: Unsigned division by a power of 2

For C variables x and k with unsigned values x and k, such that $0 \leq k < w$, the C expression x >> k yields the value $\lfloor x/2^k \rfloor$.

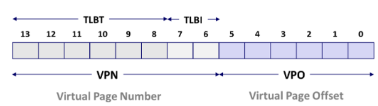
PRINCIPLE: Two's-complement division by a power of 2, rounding up

Let C variables x and k have two's-complement value x and unsigned value k, respectively, such that $0 \leq k < w$. The C expression (x + (1 << k) - 1) >> k, when the shift is performed arithmetically, yields the value $\lceil x/2^k \rceil$.

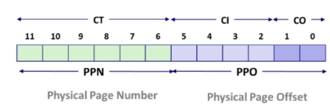
Review of Symbols



- **Basic Parameters**
  - **N = 2^n**: Number of addresses in virtual address space
  - **M = 2^m**: Number of addresses in physical address space
  - **P = 2^p** : Page size (bytes)
- **Components of the *virtual address* (VA)**
  - **TLBI**: TLB index
  - **TLBT**: TLB tag
  - **VPO**: Virtual page offset
  - **VPN**: Virtual page number

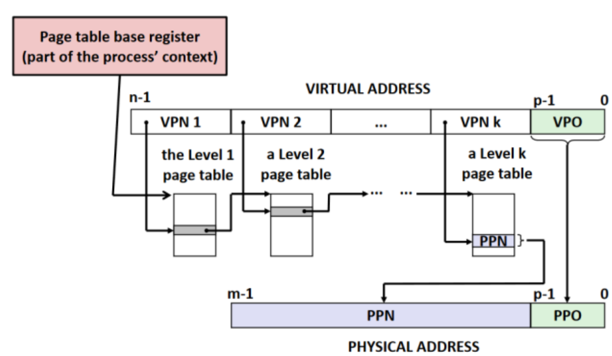


- **Components of the *physical address* (PA)** (bits per field for our simple example)
  - **PPO**: Physical page offset (same as VPO)
  - **PPN**: Physical page number
  - **CO**: Byte offset within cache line
  - **CI**: Cache index
  - **CT**: Cache tag

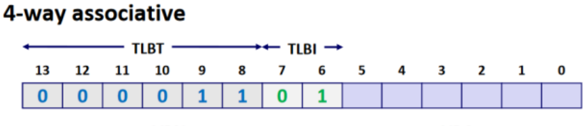


Translating with a k-level Page Table

- **Having multiple levels greatly reduces page table size**

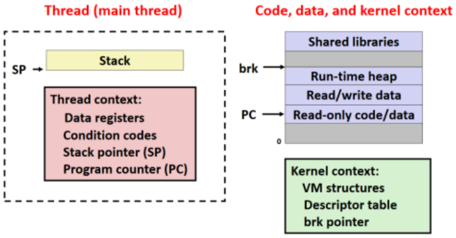


- **16 entries**
- **4-way associative**



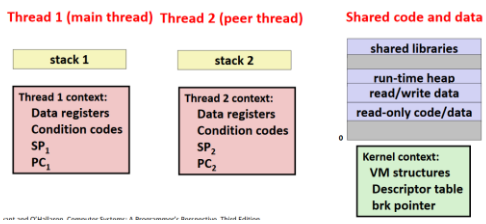
Processes and such

- **Process = thread + code, data, and kernel context**

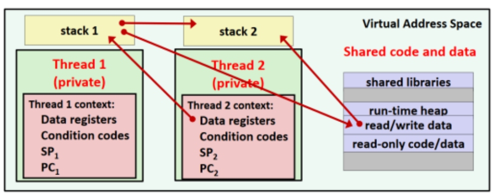


A Process With Multiple Threads

- **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)



- **Separation of data is not strictly enforced:**
  - Register values are truly separate and protected, but…
  - Any thread can read and write the stack of any other thread




```
long* p = Malloc(sizeof(long));
*p = i;
Pthread_create(&tids[i],
               NULL,
               thread,
               (void *)p);

(i = 0; i < N; i++)
```

- Use malloc to create a per thread heap allocated place in memory for the argument

- Creating and reaping threads
  - `pthread_create()`
  - `pthread_join()`
- Determining your thread ID
  - `pthread_self()`
- Terminating threads
  - `pthread_cancel()`
  - `pthread_exit()`
  - `exit()` [terminates all threads]
  - `return` [terminates current thread]
- Synchronizing access to shared variables
  - `pthread_mutex_init`
  - `pthread_mutex_[un]lock`

```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"
void *thread(void *vargp);

int main(int argc, char** argv)
{
    pthread_t tid;
    Pthread_create(&tid, NULL, thread, NULL);
    Pthread_join(tid, NULL);
    return 0;
}
```

hello.c

Thread ID

Thread attributes (usually NULL)

Thread routine

Thread arguments (void *p)

Return value (void **p)

```
void *thread(void *vargp) /* thread routine */
{
    printf("Hello, world!\n");
    return NULL;
}
```

hello.c

- **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.

Shared Variable Analysis

- **Which variables are shared?**

Variable instance	*Referenced by main thread?*	*Referenced by peer thread 0?*	*Referenced by peer thread 1?*
ptr	yes	yes	yes
cnt	no	yes	yes
i.m	yes	no	no
msgs.m	yes	yes	yes
myid.p0	no	yes	no
myid.p1	no	no	yes

```
char **ptr;  /* global var */
int main(int main, char *argv[]) {
  long i; pthread_t tid;
  char *msgs[2] = {"Hello from foo",
                   "Hello from bar" };
    ptr = msgs;
    for (i = 0; i < 2; i++)
        Pthread_create(&tid,
            NULL, thread,(void *)i);
    Pthread_exit(NULL);}
```

```
void *thread(void *vargp)
{
  long myid = (long)vargp;
  static int cnt = 0;

  printf("[%ld]:  %s (cnt=%d)\n",
         myid, ptr[myid], ++cnt);
  return NULL;
}
```

- `ptr`, `cnt`, and `msgs` are shared
- `i` and `myid` are *not* shared

Issues With Thread-Based Servers

- **Must run "detached" to avoid memory leak**
  - At any point in time, a thread is either *joinable* or *detached*
  - *Joinable* thread can be reaped and killed by other threads
    - must be reaped (with `pthread_join`) to free memory resources
  - *Detached* thread cannot be reaped or killed by other threads
    - resources are automatically reaped on termination
  - Default state is joinable
    - use `pthread_detach(pthread_self())` to make detached
- **Must be careful to avoid unintended sharing**
  - For example, passing pointer to main thread's stack
    - `Pthread_create(&tid, NULL, thread, (void *)&connfd);`
- **All functions called by a thread must be *thread-safe***

Appendix: Writing signal handlers

- **G1. Call only async-signal-safe functions in your handlers.**
  - Do not call `printf`, `sprintf`, `malloc`, `exit`! Doing so can cause deadlocks, since these functions may require global locks.
  - We've provided you with `sio_printf` which you can use instead.
- **G2. Save and restore `errno` on entry and exit.**
  - If not, the signal handler can corrupt code that tries to read `errno`.
  - The driver will print a warning if `errno` is corrupted.
- **G3. Temporarily block signals to protect shared data.**
  - This will prevent race conditions when writing to shared data.
- **Avoid the use of global variables in tshlab.**

Synchronization: Concurrency Issues

Avoiding Deadlock

Acquire shared resources in same order

```
int main(int argc, char** argv)
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], NULL);
    printf("cnt=%d\n", cnt);
    return 0;
}
```

```
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
        P(&mutex[0]); P(&mutex[1]);
        cnt++;
        V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}
```

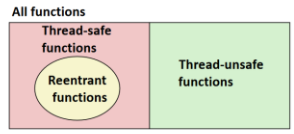
Tid[0]:	Tid[1]:
$P(s_0)$;	$P(s_0)$;
$P(s_1)$;	$P(s_1)$;
cnt++;	cnt++;
$V(s_0)$;	$V(s_1)$;
$V(s_1)$;	$V(s_0)$;

- **Classes of thread-unsafe functions:**
  - Class 1: Functions that do not protect shared variables
  - Class 2: Functions that keep state across multiple invocations
  - Class 3: Functions that return a pointer to a static variable
  - Class 4: Functions that call thread-unsafe functions
- **Failing to protect shared variables**
  - Fix: Use *P* and *V* semaphore operations (or mutex)
  - Example: `goodcnt.c`
  - Issue: Synchronization operations will slow down code

Reentrant Functions

- **Def: A function is *reentrant* iff it accesses no shared variables when called by multiple threads.**
  - Important subset of thread-safe functions
    - Require no synchronization operations
    - Only way to make a Class 2 function thread-safe is to make it reentrant (e.g., `rand_r`)

All functions



Semaphores

- ***Semaphore:*** **non-negative global integer synchronization variable**
- **Manipulated by *P* and *V* operations:**
  - *P(s):* [`while (s == 0) wait(); s--;`]
    - Dutch for "Proberen" (test)
  - *V(s):* [`s++;`]
    - Dutch for "Verhogen" (increment)
- **OS kernel guarantees that operations between brackets [ ] are executed indivisibly**
  - Only one *P* or *V* operation at a time can modify s.
  - When `while` loop in *P* terminates, only that *P* can decrement `s`
- **Semaphore invariant: *(s >= 0)***
- *Mutex:* binary semaphore used for mutual exclusion
  - P operation: "locking" the mutex
  - V operation: "unlocking" or "releasing" the mutex
  - *"Holding"* a mutex: locked and not yet unlocked.
- **Define and initialize a mutex for the shared variable `cnt`:**

```
volatile long cnt = 0;  /* Counter */
sem_t mutex;            /* Semaphore that protects cnt */

sem_init(&mutex, 0, 1); /* mutex = 1 */
```

- **Surround critical section with *P* and *V*:**

```
for (i = 0; i < niters; i++) {
    P(&mutex);
    cnt++;
    V(&mutex);
}
```

goodcnt.c

```
linux> ./goodcnt 10000
OK cnt=20000
linux> ./goodcnt 10000
OK cnt=20000
linux>
```

- **Define and initialize a mutex for the shared variable `cnt`:**

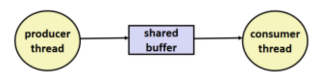
```
volatile long cnt = 0;  /* Counter */
pthread_mutex_t mutex;
pthread_mutex_init(&mutex, NULL); // No special attributes
```

- **Surround critical section with *lock* and *unlock*:**

```
for (i = 0; i < niters; i++) {
    pthread_mutex_lock(&mutex);
    cnt++;
    pthread_mutex_unlock(&mutex);
```

```
linux> ./goodmcnt 10000
OK cnt=20000
linux> ./goodmcnt 10000
OK cnt=20000
```

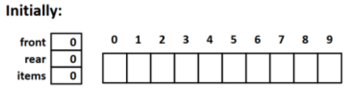
Producer-Consumer Problem



- **Common synchronization pattern:**
  - Producer waits for empty ***slot***, inserts item in buffer, and notifies consumer
  - Consumer waits for ***item***, removes it from buffer, and notifies producer

Circular Buffer (n = 10)

- **Store elements in array of size n**
- **items: number of elements in buffer**
- **Empty buffer:**
  - front = rear
- **Nonempty buffer**
  - rear: index of most recently inserted element
  - front: (index of next element to remove – 1) mod n
- **Initially:**




```
void sbuf_init(sbuf_t *sp, int n)
{
    sp->buf = Calloc(n, sizeof(int));
    sp->n = n;                       /* Buffer holds max of n items */
    sp->front = sp->rear = 0;        /* Empty buffer iff front == rear */
    Sem_init(&sp->mutex, 0, 1); /* Binary semaphore for locking */
    Sem_init(&sp->slots, 0, n); /* Initially, buf has n empty slots */
    Sem_init(&sp->items, 0, 0); /* Initially, buf has zero items */
}
```

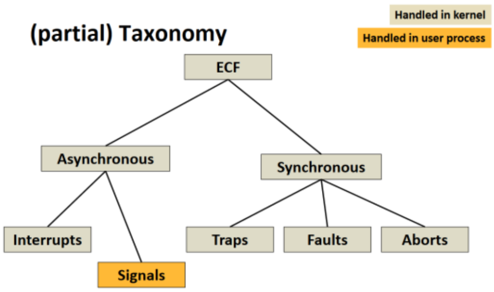
```
/* Insert item onto the rear of shared buffer sp */
void sbuf_insert(sbuf_t *sp, int item)
{
    P(&sp->slots);                  /* Wait for available slot */
    P(&sp->mutex);                  /* Lock the buffer         */
    if (++sp->rear >= sp->n)        /* Increment index (mod n) */
        sp->rear = 0;
    sp->buf[sp->rear] = item;       /* Insert the item         */
    V(&sp->mutex);                  /* Unlock the buffer       */
    V(&sp->items);                  /* Announce available item */
}
```

sbuf.c

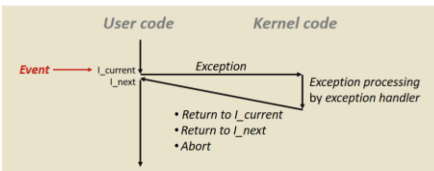
```
/* Remove and return the first item from buffer sp */
int sbuf_remove(sbuf_t *sp)
{
    int item;
    P(&sp->items);                  /* Wait for available item */
    P(&sp->mutex);                  /* Lock the buffer         */
    if (++sp->front >= sp->n)       /* Increment index (mod n) */
        sp->front = 0;
    item = sp->buf[sp->front];      /* Remove the item         */
    V(&sp->mutex);                  /* Unlock the buffer       */
    V(&sp->slots);                  /* Announce available slot */
    return item;
}
```

sbuf.c

ECF

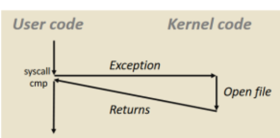


- An *exception* is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)
  - Kernel is the memory-resident part of the OS
  - Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request completes, typing Ctrl-C



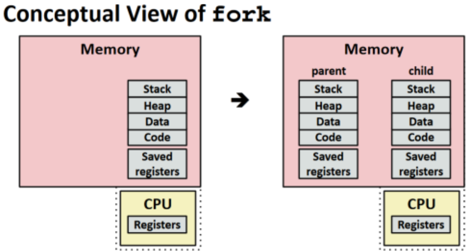
- User calls: `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

```
00000000000e5d70 <__open>:
...
e5d79:  b8 02 00 00 00    mov  $0x2,%eax  # open is syscall #2
e5d7e:  0f 05             syscall         # Return value in %rax
e5d80:  48 3d 01 f0 ff ff  cmp  $0xfffffffffffff001,%rax
...
e5dfa:  c3                retq
```



- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

Conceptual View of `fork`



WAITPID

pid_t wait(int **stat_loc*);
pid_t waitpid(pid_t *pid*, **int** **stat_loc*, **int** *options*);

If *pid* is equal to (**pid_t**)-1, *status* is requested for any child process. In this respect, *waitpid*() is then equivalent to *wait*().

If *pid* is greater than 0, it specifies the process ID of a single child process for which *status* is requested.

If *pid* is 0, *status* is requested for any child process whose process group ID is equal to that of the calling process.

If *pid* is less than (**pid_t**)-1, *status* is requested for any child process whose process group ID is equal to the absolute value of *pid*.

WIFEXITED(*stat_val*)

Evaluates to a non-zero value if *status* was returned for a child process that terminated normally.

WEXITSTATUS(*stat_val*)

If the value of WIFEXITED(*stat_val*) is non-zero, this macro evaluates to the low-order 8 bits of the *status* argument that the child process passed to *_exit*() or *exit*(), or the value the child process returned from *main*().

WIFSIGNALED(*stat_val*)

Evaluates to a non-zero value if *status* was returned for a child process that terminated due to the receipt of a signal that was not caught (see <*signal.h*>).

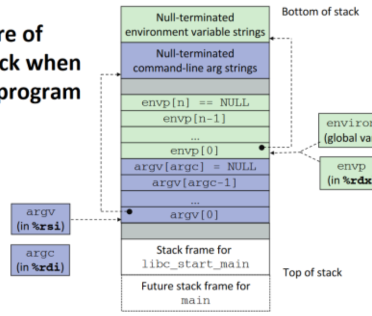
Return Value

If *wait*() or *waitpid*() returns because the status of a child process is available, these functions shall return a value equal to the process ID of the child process for which *status* is reported. If *wait*() or *waitpid*() returns due to the delivery of a signal to the calling process, -1 shall be returned and *errno* set to [EINTR]. If *waitpid*() was invoked with WNOHANG set in *options*, it has at least one child process specified by *pid* for which *status* is not available, and *status* is not available for any process specified by *pid*, 0 is returned. Otherwise, (**pid_t**)-1 shall be returned, and *errno* set to indicate the error.

EXECVE

- `int execve(char *filename, char *argv[], char *envp[])`
- Loads and runs in the current process:
  - Executable file `filename`
    - Can be object file or script file beginning with `#!interpreter` (e.g., `#!/bin/bash`)
  - …with argument list `argv`
    - By convention `argv[0]==filename`
  - …and environment variable list `envp`
    - "name=value" strings (e.g., `USER=droh`)
    - `getenv`, `putenv`, `printenv`
- Overwrites code, data, and stack
  - Retains PID, open files and signal context
- Called **once** and **never** returns
  - …except if there is an error

Structure of the stack when a new program starts



Signal Handling

- The `signal` function modifies the default action associated with the receipt of signal `signum`:
  - `handler_t *signal(int signum, handler_t *handler)`
- Different values for `handler`:
  - SIG_IGN: ignore signals of type `signum`
  - SIG_DFL: revert to the default action on receipt of signals of type `signum`
  - Otherwise, `handler` is the address of a user-level *signal handler*
- Implicit blocking mechanism
  - Kernel blocks any pending signals of type currently being handled
  - e.g., a SIGINT handler can't be interrupted by another SIGINT
- Explicit blocking and unblocking mechanism
  - `sigprocmask` function

```
sigset_t mask, prev_mask;

Sigemptyset(&mask);
Sigaddset(&mask, SIGINT);

/* Block SIGINT and save previous blocked set */
Sigprocmask(SIG_BLOCK, &mask, &prev_mask);
:
   /* Code region that will not be interrupted by SIGINT */
:
/* Restore previous blocked set, unblocking SIGINT */
Sigprocmask(SIG_SETMASK, &prev_mask, NULL);
```

Guidelines for Writing Safe Handlers

- G0: Keep your handlers as simple as possible
  - e.g., set a global flag and return
- G1: Call only async-signal-safe functions in your handlers
  - `printf`, `sprintf`, `malloc`, and `exit` are not safe!
- G2: Save and restore `errno` on entry and exit
  - So that other handlers don't overwrite your value of `errno`
- G3: Protect accesses to shared data structures by temporarily blocking all signals
  - To prevent possible corruption
- G4: Declare global variables as `volatile`
  - To prevent compiler from storing them in a register
- G5: Declare global flags as `volatile sig_atomic_t`
  - *flag*: variable that is only read or written (e.g. flag = 1, not flag++)
  - Flag declared this way does not need to be protected like other globals
- Function is *async-signal-safe* if either reentrant (e.g., all variables stored on stack frame, CS:APP3e 12.7.2) or non-interruptible by signals
- Posix guarantees 117 functions to be async-signal-safe
  - Source: "`man 7 signal-safety`"
  - Popular functions on the list:
    - `_exit`, `write`, `wait`, `waitpid`, `sleep`, `kill`

```
while (n--) {
    Sigprocmask(SIG_BLOCK, &mask_one, &prev_one); /* Block SIGCHLD */
    if ((pid = Fork()) == 0) { /* Child process */
        Sigprocmask(SIG_SETMASK, &prev_one, NULL); /* Unblock SIGCHLD */
        Execve("/bin/date", argv, NULL);
    }
    Sigprocmask(SIG_BLOCK, &mask_all, NULL); /* Parent process */
    addjob(pid);  /* Add the child to the job list */
    Sigprocmask(SIG_SETMASK, &prev_one, NULL);  /* Unblock SIGCHLD */
}
exit(0);
```

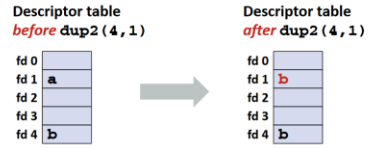
Preventing Races

- `int sigsuspend(const sigset_t *mask)`
- Equivalent to atomic (uninterruptable) version of:

```
sigprocmask(SIG_SETMASK, &mask, &prev);
pause();
sigprocmask(SIG_SETMASK, &prev, NULL);
```

FILE IO

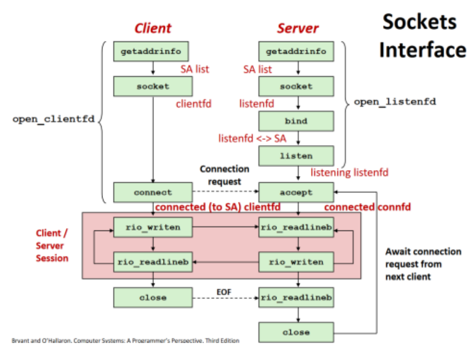
- Answer: By calling the `dup2(oldfd, newfd)` function
  - Copies (per-process) descriptor table entry `oldfd` to entry `newfd`



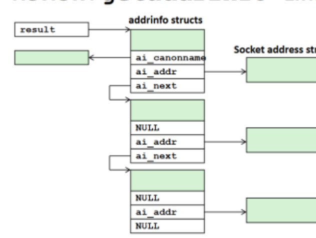
- When to use standard I/O
  - When working with disk or terminal files
- When to use raw Unix I/O
  - *Inside signal handlers, because Unix I/O is async-signal-safe*

Network

Sockets Interface



Review: `getaddrinfo` Linked List



- Clients: walk this list, trying each socket address in turn, until the calls to `socket` and `connect` succeed.
- Servers: walk the list until calls to `socket` and `bind` succeed.

OTHER

Snoopy Caches
- invalid : cannot use value
- shared : readable cpy
- exclusive : writable cpy
start with E → S

VM locality
- working set size < main memory
good performance
- working set size > main memory
thrashing

KB ⇒ 2^{10}

- deadlock : nothing can proceed (need locks)
- livelock : infinite loop
- starvation : unfairness, one has priority

Garbage collection
- mark & sweep : mark all connected to roots
sweep all allocated and not marked.