15213 Recitation Section C

Shimin Chen

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Outline

- Threads
- Synchronization
- Thread-safety of Library Functions

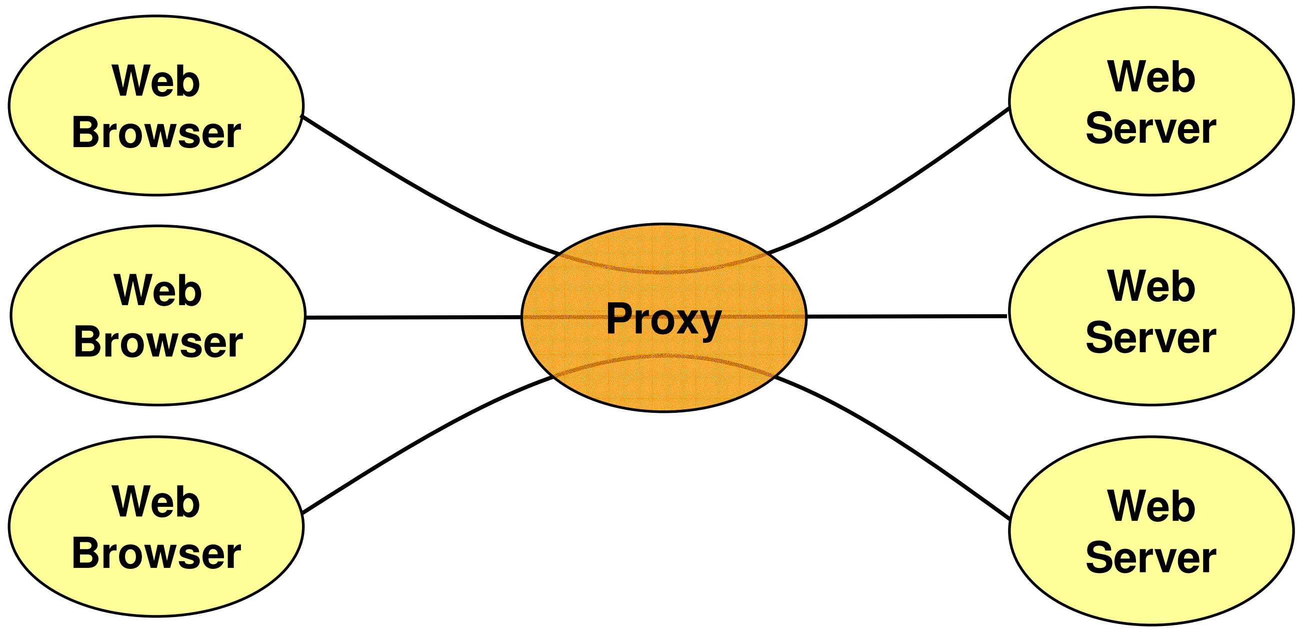
Important Dates

- Lab 7 *Proxy:* due on Thursday, Dec 5

- Final Exam: Tuesday, Dec 17

Concurrent Servers

- Iterative servers can only serve one client at a time
- Concurrent servers are able to handle multiple requests in parallel
- Required by L7 Part II



Three Ways for Creating Concurrent Servers

1. Processes
   - Fork a child process for every incoming client connection
   - Difficult to share data among child processes
2. Threads
   - Create a thread to handle every incoming client connection
   - Our focus today
3. I/O multiplexing with Unix `select()`
   - Use `select()` to notice pending socket activity
   - Manually interleave the processing of multiple open connections
   - More complex!
     - ~ implementing your own app-specific thread package!

Traditional View of a Process

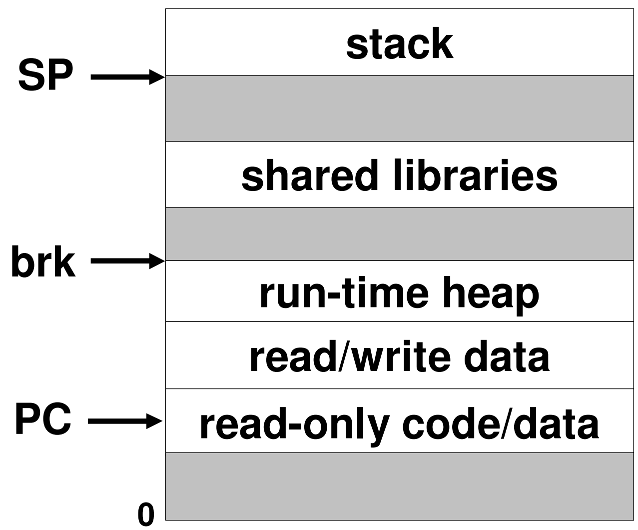
- Process = process context + code, data, and stack

Process context

Program context:
- Data registers
- Condition codes
- Stack pointer (SP)
- Program counter (PC)

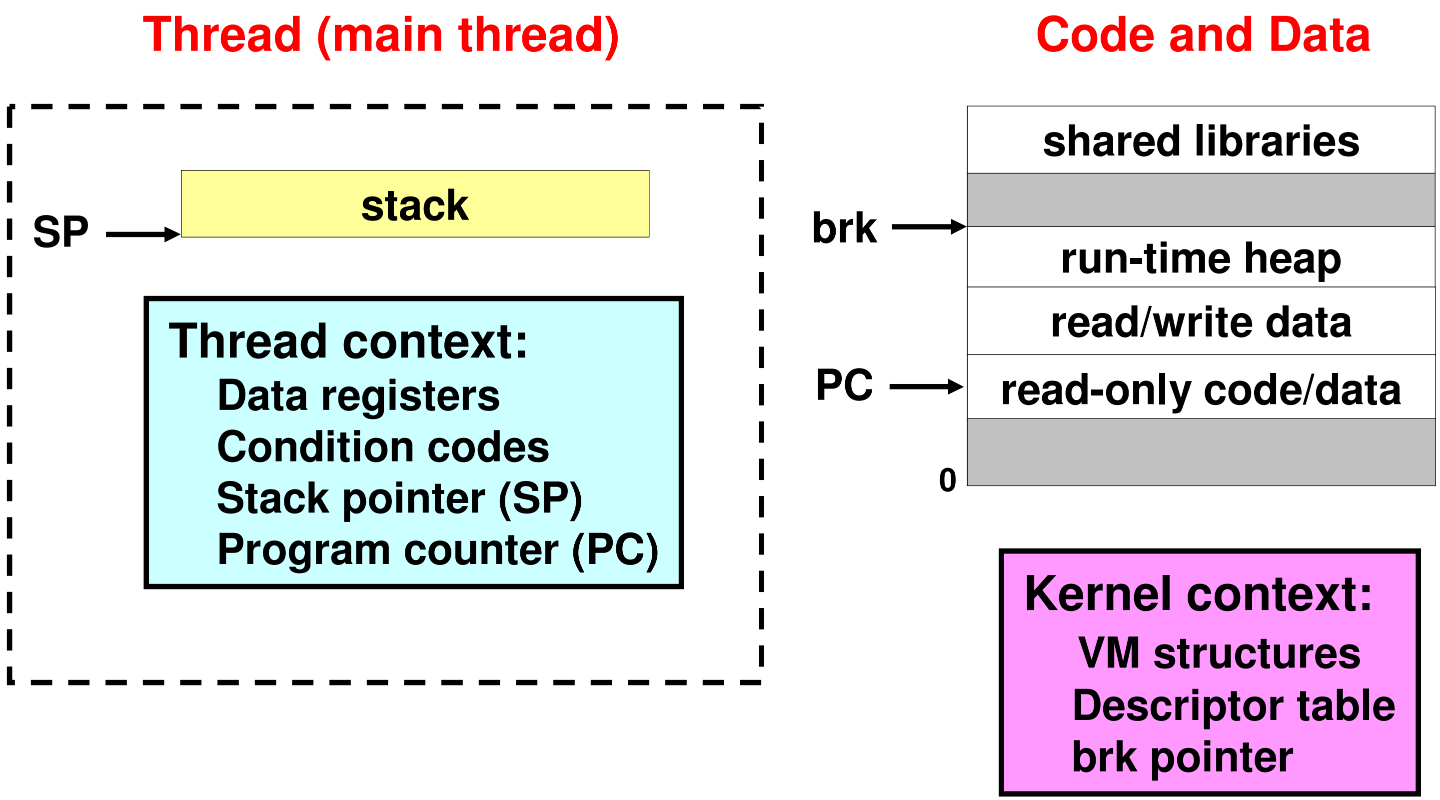
Kernel context:
- VM structures
- Descriptor table
- brk pointer

Code, data, and stack



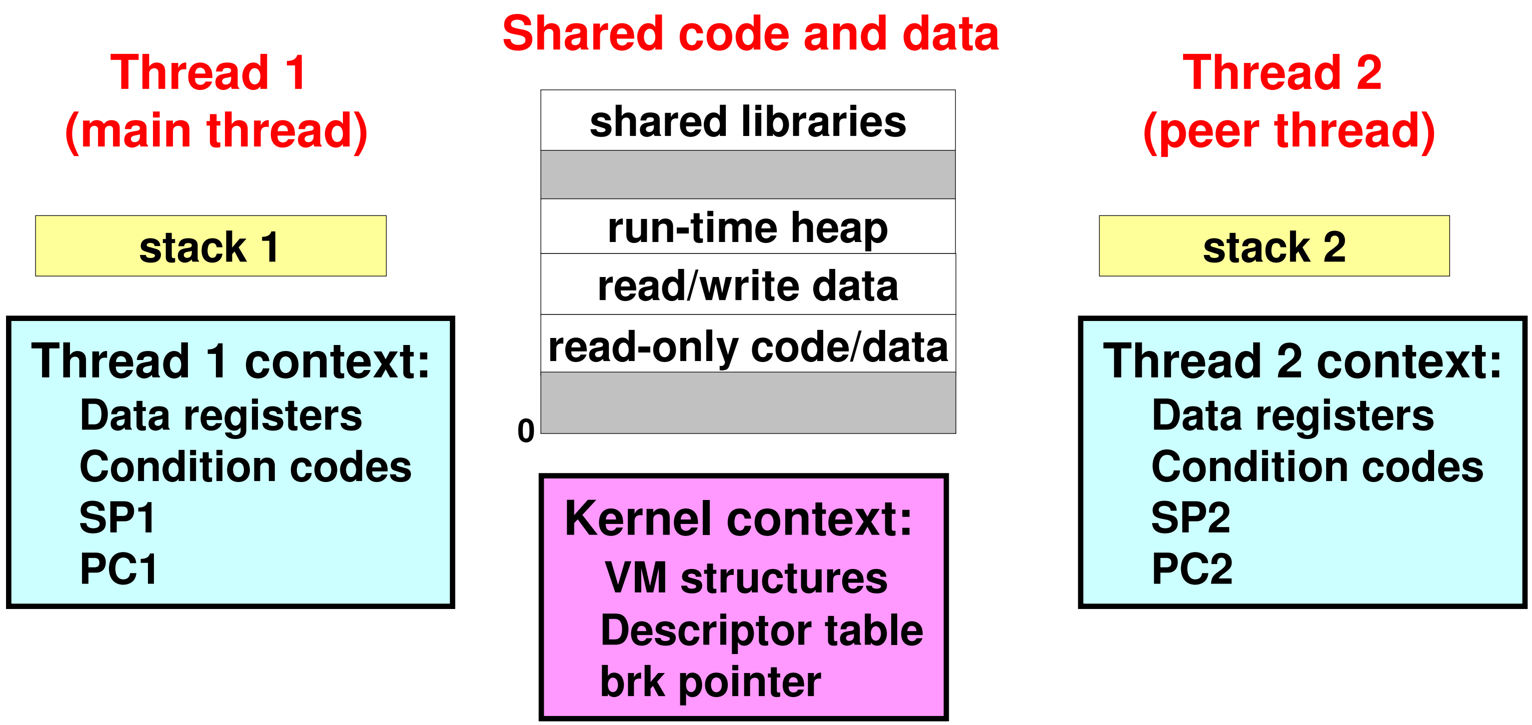
Alternate View of a Process

- 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 (instruction flow)
  - Each thread shares the same code, data, and kernel context
  - Each thread has its own thread ID (TID)



Threads vs. Processes

- How threads and processes are similar
  - Each has its own logical control flow.
  - Each can run concurrently.
  - Each is context switched.
- How threads and processes are different
  - Threads share code and data, processes (typically) do not.
  - Threads are somewhat less expensive than processes.
    - Process control (creating and reaping) is twice as expensive as thread control.
    - Linux/Pentium III numbers:
      - ~20K cycles to create and reap a process.
      - ~10K cycles to create and reap a thread.

Posix Threads (Pthreads) Interface

- Standard interface for ~60 functions
  - 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`**
    - **`pthread_cond_init`**
    - **`pthread_cond_[timed]wait`**

The Pthreads "hello, world" Program

```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"

void *thread(void *vargp);

int main() {
  pthread_t tid;

  Pthread_create(&tid, NULL, thread, NULL);
  Pthread_join(tid, NULL);
  exit(0);
}

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

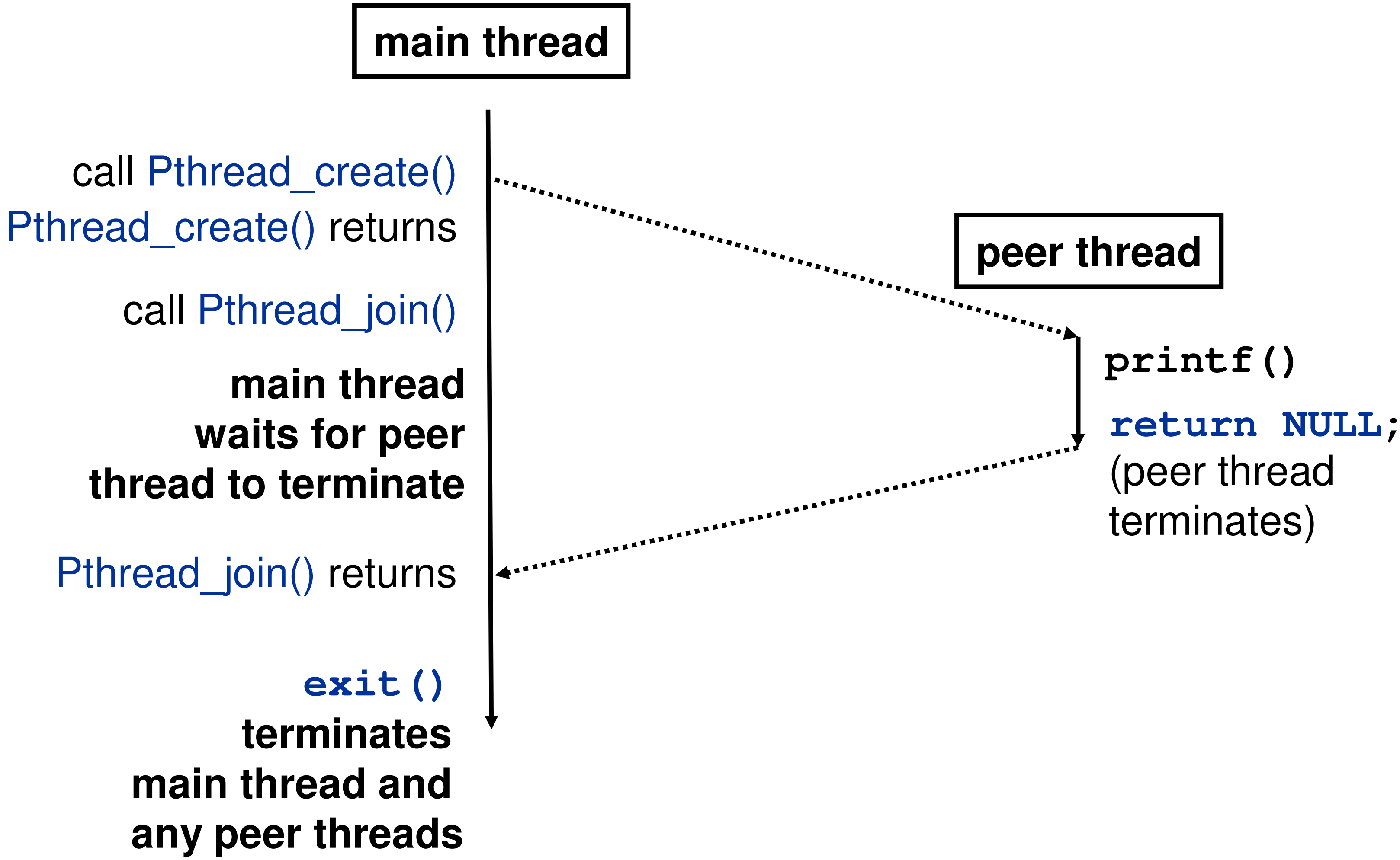
Thread attributes (usually NULL)

*Thread arguments (void *p)*

*return value (void **p)*

Upper case Pthread_xxx checks errors

Execution of Threaded“hello, world”



Thread-Based Concurrent Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, *connfdp, port, clientlen;
    struct sockaddr_in clientaddr;
    pthread_t tid;

    if (argc != 2) {
        fprintf(stderr, "usage: %s <port>\n", argv[0]);
        exit(0);
    }
    port = atoi(argv[1]);

    listenfd = open_listenfd(port);
    while (1) {
        clientlen = sizeof(clientaddr);
        connfdp = Malloc(sizeof(int));
        *connfdp = Accept(listenfd,(SA *)&clientaddr,&clientlen);
        Pthread_create(&tid, NULL, thread, connfdp);
    }
}
```

Thread-Based Concurrent Server (cont)

```
* thread routine */
void *thread(void *vargp)
{
    int connfd = *((int *)vargp);

    Pthread_detach(pthread_self());
    Free(vargp);

    echo_r(connfd); /* thread-safe version of echo() */
    Close(connfd);
    return NULL;
}
```

?

Issue 1: Detached Threads

- 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.

- *Why should we use detached threads?*
  - *pthread_join blocks the calling thread*

Issue 2: Avoid Unintended Sharing

```
connfdp = Malloc(sizeof(int));
*connfdp = Accept(listenfd,(SA *)&clientaddr,&clientlen);
Pthread_create(&tid, NULL, thread, connfdp);
```

- For example, what happens if we pass the address of connfd to the thread routine as in the following code?

```
connfd = Accept(listenfd,(SA *)&clientaddr,&clientlen);
Pthread_create(&tid, NULL, thread, (void *)&connfd);
```

Issue 3: Thread-safe

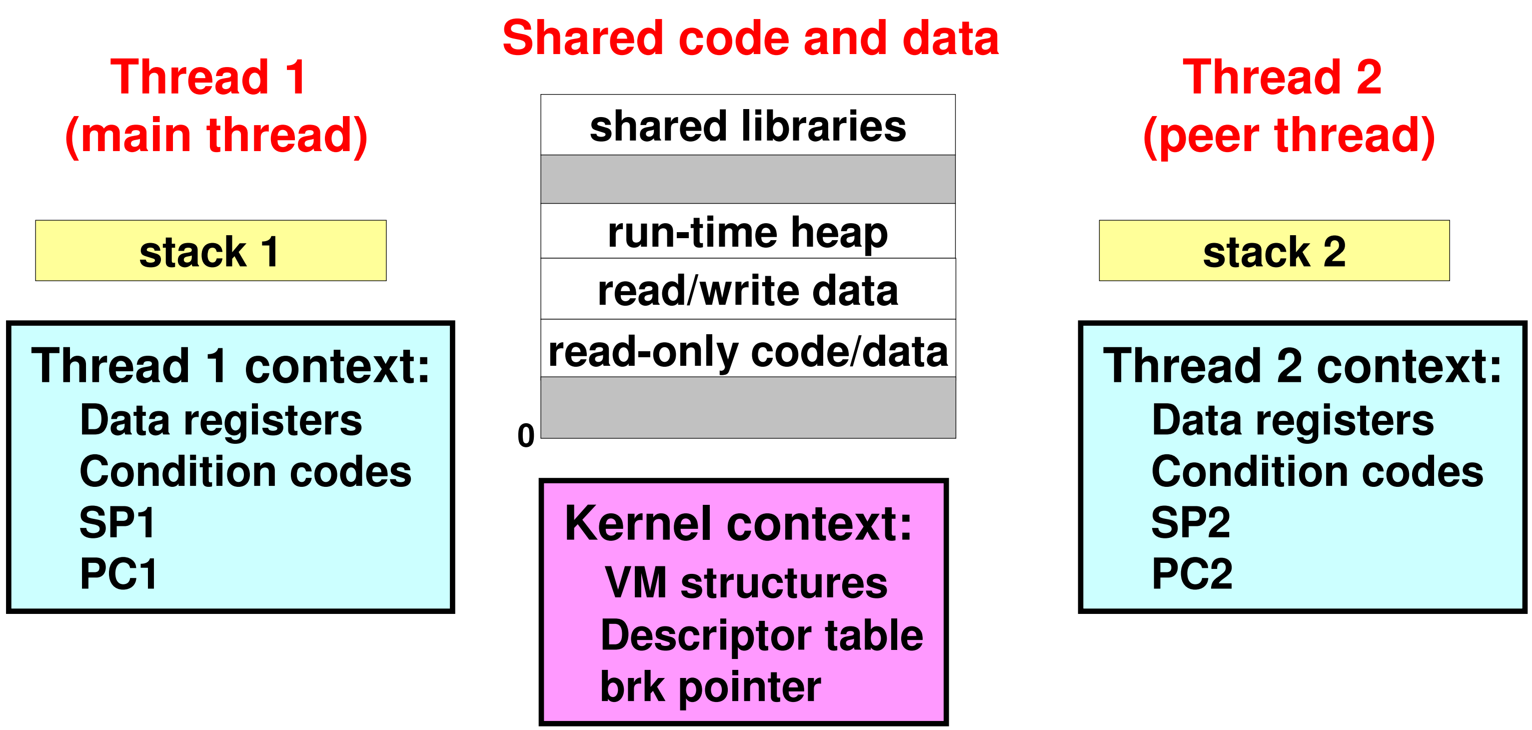
- Easy to share data structures between threads
- But we need to do this correctly!
- Recall the shell lab:
  - Job data structures
  - Shared between main process and signal handler
- Need ways to synchronize multiple control of flows

Threads Memory Model

- Conceptual model:
  - Each thread runs in the context of a process.
  - Each thread has its own separate thread context.
    - Thread ID, stack, stack pointer, program counter, condition codes, and general purpose registers.
  - All threads share the remaining process context.
    - Code, data, heap, and shared library segments of the process virtual address space.
    - Open files and installed handlers

Shared Variables in Conceptual Model

- global variables are shared
- stack variables are private



Caveats of Conceptual Models

- In practice, any thread can read and write the stack of any other thread.
- So one can use a global pointer to point to a stack variable. Then all threads can access the stack variable.
- But this is not a good programming practice.
- More details in this Thursday's lecture

Synchronization

- If multiple threads want to access a shared global data structure, we need to synchronize their accesses.
- Ways to do synchronization:
  - Semaphores
  - Mutex and conditions
  - Etc.

Synchronizing With Semaphores

- *Classic solution*: Dijkstra's P and V operations on *semaphores.*
  - *semaphore:* non-negative integer synchronization variable.
    - P(s): [`while (s == 0) wait(); s--;`]
      - Dutch for "Proberen" (test)
    - V(s): [`s++;`]
      - Dutch for "Verhogen" (increment)
  - OS 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 decrements.
- Semaphore invariant: *(s >= 0)*

POSIX Semaphores (in csapp.c)

```
/* initialize semaphore sem to value */
/* pshared=0 if thread, pshared=1 if process */
void Sem_init(sem_t *sem, int pshared, unsigned int value) {
  if (sem_init(sem, pshared, value) < 0)
    unix_error("Sem_init");
}

/* P operation on semaphore sem */
void P(sem_t *sem) {
  if (sem_wait(sem))
    unix_error("P");
}

/* V operation on semaphore sem */
void V(sem_t *sem) {
  if (sem_post(sem))
    unix_error("V");
}
```

Sharing With POSIX Semaphores

```
#include "csapp.h"
#define NITERS 10000000

unsigned int cnt; /* counter */
sem_t sem;        /* semaphore */

int main() {
    pthread_t tid1, tid2;

    Sem_init(&sem, 0, 1);

    /* create 2 threads and wait */
    ......

    exit(0);
}
```

```
/* thread routine */
void *count(void *arg)
{
  int i;

  for (i=0;i<NITERS;i++){
        P(&sem);
        cnt++;
        V(&sem);
  }
  return NULL;
}
```

Thread-safety of Library Functions

- All functions in the Standard C Library (at the back of your K&R text) are thread-safe.
  - Examples: **`malloc`**, **`free`**, **`printf`**, **`scanf`**
- Most Unix system calls are thread-safe, with a few exceptions:

Thread-unsafe function	Class	Reentrant version
`asctime`	3	`asctime_r`
`ctime`	3	`ctime_r`
`gethostbyaddr`	3	`gethostbyaddr_r`
`gethostbyname`	3	`gethostbyname_r`
`inet_ntoa`	3	`(none)`
`localtime`	3	`localtime_r`
`rand`	2	`rand_r`

Thread-Unsafe Functions: Fixes

- Return a ptr to a **`static`** variable.
- Fixes:
  1. Rewrite code so caller passes pointer to **`struct`**.
     - Issue: Requires changes in caller and callee.

```
struct hostent
*gethostbyname(char name)
{
  static struct hostent h;
  <contact DNS and fill in h>
  return &h;
}
```

```
hostp = Malloc(...));
gethostbyname_r(name, hostp);
```

Thread-Unsafe Functions: Fixes

- Return a ptr to a **`static`** variable.
- Fixes:

  2. *Lock-and-copy*

     - Issue: Requires only simple changes in caller
     - However, caller must free memory.

```
struct hostent
*gethostbyname(char name)
{
  static struct hostent h;
  <contact DNS and fill in h>
  return &h;
}
```

```
struct hostent
*gethostbyname_ts(char *p)
{
  struct hostent *q = Malloc(...);
  P(&mutex); /* lock */
  p = gethostbyname(name);
  *q = *p;    /* copy */
  V(&mutex);
  return q;
}
```

Summary

- Threading is a clean and efficient way to implement concurrent server
- We need to synchronize multiple threads for concurrent accesses to shared variables
  - Semaphore is one way to do this
  - Thread-safety is the difficult part of thread programming