15-213

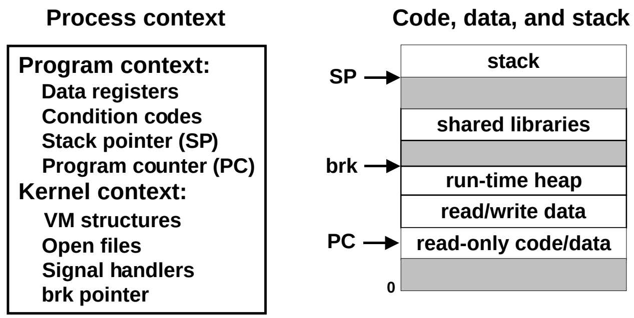
"The course that gives CMU its Zip!"

Concurrency I: Threads
Nov 9, 2000

Topics
- Thread concept
- Posix threads (Pthreads) interface
- Linux Pthreads implementation
- Concurrent execution
- Sharing data

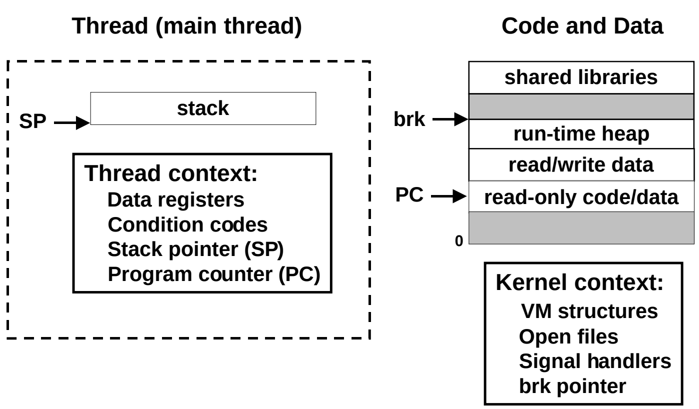
Traditional view of a process

Process = process context + code, data, and stack



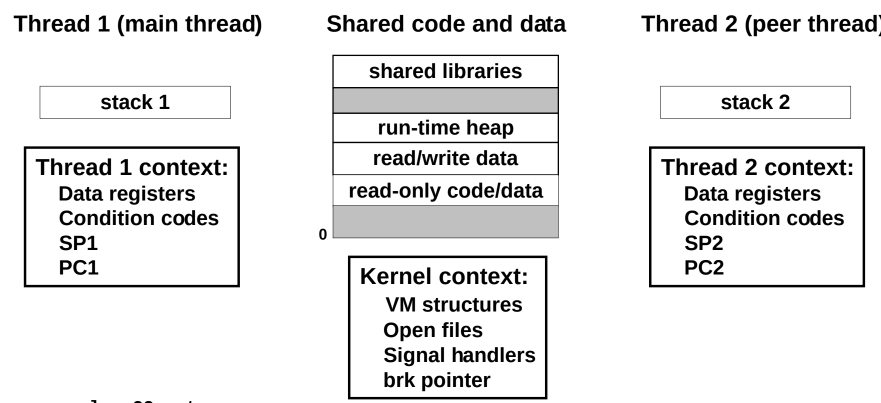
Modern view of a process

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 (sequence of PC values)
- Each thread shares the same code, data, and kernel context
- Each thread has its own thread id (tid)

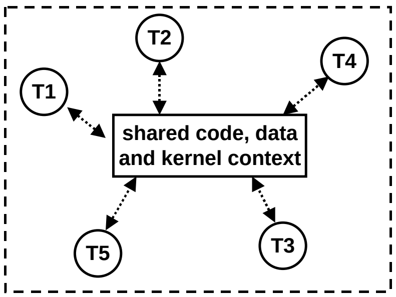


Logical view of threads

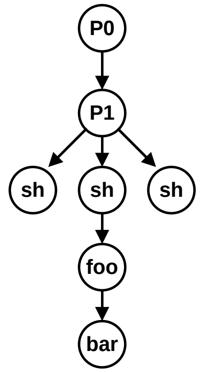
Threads associated with a process form a pool of peers.

- unlike processes which form a tree hierarchy

Threads associated with process foo



Process hierarchy



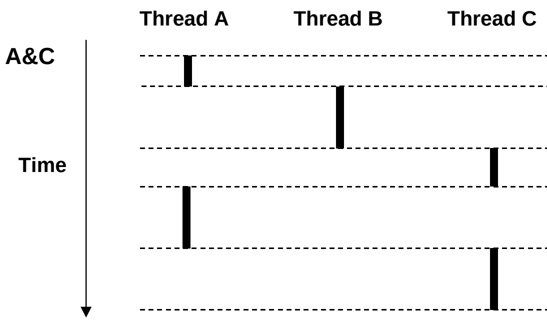
Concurrent thread execution

Two threads *run concurrently* (*are concurrent)* if their logical flows overlap in time.

Otherwise, they are *sequential.*

Examples:

- Concurrent: A & B, A&C
- Sequential: B & C



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.

Threads are a unifying abstraction for exceptional control flow

Exception handler

- A handler can be viewed as a thread
- Waits for a "signal" from CPU
- Upon receipt, executes some code, then waits for next "signal"

Process

- A process is a thread + shared code, data, and kernel context.

Signal handler

- A signal handler can be viewed as a thread
- Waits for a signal from the kernel or another process
- Upon receipt, executes some code, then waits for next signal.

Posix threads (Pthreads) interface

Pthreads: **Standard interface for ~60 functions that manipulate threads from C programs.**

- Creating and reaping threads.
  - `pthread_create`
  - `pthread_join`
- Determining your thread ID
  - `pthread_self`
- Terminating threads
  - `pthread_cancel`
  - `pthread_exit`
  - `exit()` [terminates all threads] , `ret` [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

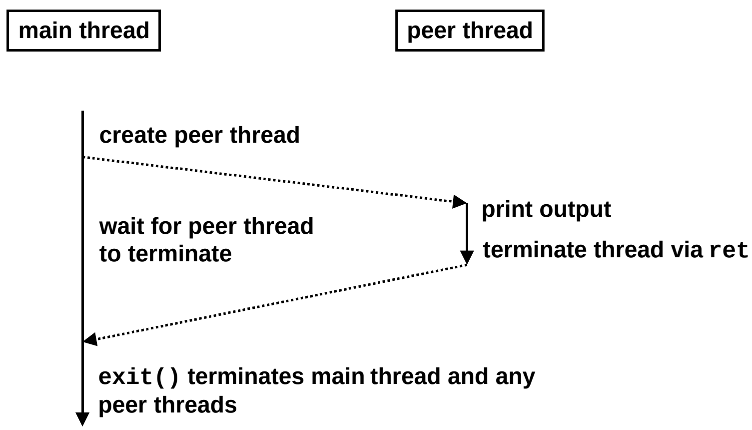
```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include <ics.h>

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)*

Execution of “hello, world”



Unix vs Posix error handling

Unix-style error handling (Unix syscalls)

- if error: return -1 and set `errno` variable to error code.
- if OK: return useful result as value >= 0.

```
if ((pid = wait(NULL)) < 0) {
   perror("wait");
   exit(0);
}
```

Posix-style error handling (newer Posix functions)

- if error: return nonzero error code, zero if OK
- useful results are passed back in an argument.

```
if ((rc = pthread_join(tid, &retvalp)) != 0) {
   printf(”pthread_create: %s\n", strerror(rc));
   exit(0);
}
```

Suggested error handling macros

Error checking crucial, but cluttered. Use these to simplify your error checking:

```
/*
 * macro for unix-style error handling
 */
#define unix_error(msg) do {\
  printf("%s: %s\n", msg, strerror(errno));\
  exit(0);\
} while (0)
```

```
/*
 * macro for posix-style error handling
 */
#define posix_error(code,msg) do {\
  printf("%s: %s\n", msg, strerror(code));\
  exit(0);\
} while (0)
```


Pthreads wrappers

We advocate Steven's convention of providing wrappers for each system-level function call.

- wrapper is denoted by capitalizing first letter of function name.
- wrapper has identical interface as the original function.
- each wrapper does appropriate unix or posix style error checking.
- wrapper typically return nothing.
- declutters code without compromising safety.

```
/*
 * wrapper function for pthread_join
 */
void Pthread_join(pthread_t tid, void **thread_return) {
  int rc = pthread_join(tid, thread_return);
  if (rc != 0)
    posix_error(rc, "Pthread_join");
}
```


Basic thread control: create a thread

```
int pthread_create(pthread_t *tidp, pthread_attr_t *attrp,
                   void *(*routine)(void *), void *argp);
```

Creates a new peer thread

- `tidp`: thread id
- `attrp`: thread attributes (usually NULL)
- `routine`: thread routine
- `argp`: input parameters to `routine`

Akin to `fork()`

- but without the confusing "call once return twice" semantics.
- peer thread has local stack variables, but shares all global variables.

Basic thread control: join

```
int pthread_join(pthread_t tid, void **thread_return);
```

Waits for a specific peer thread to terminate, and then reaps it.

- `tid`: thread ID of thread to wait for.
- `thread_return`: object returned by peer thread via `ret` stmt

Akin to `wait` and `wait_pid` but unlike `wait` ...

- Any thread can reap any other thread (not just children)
- Must wait for a *specific* thread
  - no way to wait for *any* thread.
  - perceived by some as a flaw in the Pthreads design

Linux implementation of Pthreads

Linux implements threads in an elegant way:

- Threads are just processes that share the same kernel context.
- `fork()`: creates a child process with a new kernel context
- `clone()`: creates a child process that shares some or all of the parent's kernel context.

```
int __clone(int (*fn)(void *arg),void *child_stack,
             int flags, void *arg);
```

Creates a new process and executes function `fn` with argument `arg` in that process using the stack space pointed to by `child_stack`. Returns `pid` of new process.

`flags` determine the degree of kernel context sharing: e.g.,

CLONE_VM: share virtual address space
CLONE_FS: share file system information
CLONE_FILES: share open file descriptors

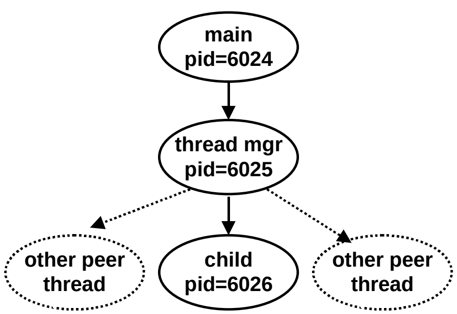
hellopid.c

The following routine will show us the process hierarchy of a Linux thread pool:

```
#include <ics.h>
void *thread(void *vargp);

int main() {
  pthread_t tid;
  printf("Hello from main thread!  tid:%ld pid:%d\n",
         pthread_self(), getpid());
  Pthread_create(&tid, NULL, thread, NULL);
  Pthread_join(tid, NULL);
  exit(0);
}

void *thread(void *vargp) {
  printf("Hello from child thread! tid:%ld pid:%d ppid:%d\n",
         pthread_self(), getpid(), getppid());
  return NULL;
}
```


Linux process hierarchy for threads

```
bass> hellopid
Hello from main thread!  tid:1024 pid:6024
Hello from child thread! tid:1025 pid:6026 ppid:6025
```



Thread manager supports thread abstraction using signals:

- `exit()`: kills all threads, regardless where it is called from
- slow system calls such as `sleep()` or `read()` block only the calling thread.

beep.c: Performing concurrent tasks

```
/*
 * beeps until the user hits a key
 */
#include <ics.h>
void *thread(void *vargp);

/* shared by both threads */
char shared = '\0';

int main() {
  pthread_t tid;
  Pthread_create(&tid, NULL,
                 thread, NULL);
  while (shared == '\0') {
    printf("BEEP\n");
    sleep(1);
  }
  Pthread_join(tid, NULL);
  printf("DONE\n");
  exit(0);
}
```

```
/* thread routine */
void *thread(void *vargp) {
  shared = getchar();
  return NULL;
}
```

badcnt.c: Sharing data between threads

```
/* bad sharing */
#include <ics.h>
#define NITERS 1000
void *count(void *arg);

struct {
  int counter;
} shared;

int main() {
  pthread_t tid1, tid2;
  Pthread_create(&tid1, NULL,
                 count, NULL);
  Pthread_create(&tid2, NULL,
                  count, NULL);
  if (shared.counter != NITERS*2)
    printf("BOOM! counter=%d\n",
            shared.counter);
  else
    printf("OK counter=%d\n",
            shared.counter);
}
```

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

  for (i=0; i<NITERS; i++) {
    val = shared.counter;
    printf("%d: %d\n",
       (int)pthread_self(),
       val);
    shared.counter = val + 1;
  }
  return NULL;
}
```

Key point:

"struct shared" is visible to all threads.

"i" and "val" are visible only to the count thread.

Running badcnt.c

Output of run 1

```
1025: 0
1025: 1
1025: 2
...
1025: 997
1025: 998
1025: 999
2050: 969
2050: 970
2050: 971
...
2050: 1966
2050: 1967
2050: 1968
BOOM! counter=1969
```

Output of run 2

```
1025: 0
1025: 1
1025: 2
...
1025: 997
1025: 998
1025: 999
2050: 712
2050: 713
2050: 714
...
2050: 1709
2050: 1710
2050: 1711
BOOM! counter=1712
```

Output of run 3

```
1025: 0
1025: 1
1025: 2
...
1025: 997
1025: 998
1025: 999
2050: 1000
2050: 1001
2050: 1002
...
2050: 1997
2050: 1998
2050: 1999
OK counter=2000
```

So what's the deal?
We must *synchronize* concurrent accesses to shared thread data
(the topic of our next lecture)