Threads

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Review

- **Process (the generic concept)**
  - A particular execution of a program
  - Separate from all other executions of that same program
  - Separate from all executions of other programs

Review — Processes in Unix, Linux, and Windows

- **a particular execution of a program PLUS**
- **an *address space* – usually protected and virtual – mapped into memory**
- **the *code* for the running program**
- **the *data* for the running program**
- **an *execution stack* and *stack pointer* (SP); also *heap***
- **the *program counter* (PC)**
- **a set of processor *registers* – general purpose and status**
- **a set of system *resources***
  - files, network connections, pipes, …
  - privileges, (human) user association, …
- **…**

Processes in Unix, Linux, and Windows (continued)

- **Evolutionary direction:– *Isolation***
- **I.e., main goal was to keep processes separate from each other**
    - Multi-user computer systems (time-sharing)
    - Independent applications
- **Communication and cooperation among processes was secondary & limited**

Processes in Unix, Linux, and Windows (continued)

- **Processes in Unix, Linux, and Windows are "heavyweight"**
  - Lots of resources
  - Expensive context switches
  - Inflexible
  - …

OS-Centric View

- **Lots of data in PCB & other data structures**
  - Even more when we study memory management
  - More than that when we study file systems, etc.
- **Processor caches a lot of information**
  - Memory Management information
  - Caches of active pages
- **Costly context switches and traps**
  - Many 10s of microseconds (even 100s of microseconds)

Application-Centric View

- **Separate processes have separate address spaces**
  - Shared memory is limited or nonexistent
  - Applications with internal concurrency are difficult
- **Isolation between independent processes *vs.* cooperating activities**
  - Fundamentally different goals

Example

- ***Web Server***
  - Need to support multiple, concurrent, independent requests pertaining to common data
- **One solution:–**
  - create several processes that execute in parallel
  - Use shared memory — **`shmget()`** — to map to the *same* address space into multiple processes
  - have the OS schedule them in parallel
- **Clumsy and inefficient**
  - *Space and time:* PCB, page tables, cloning entire process, etc.
  - *programming:* **`shmget()`** is really hard to program!

Example 2

- **Transaction processing systems**
    - E.g, airline reservations or bank ATM transactions
- **1000's of transactions *per second***
    - Very small computation per transaction
    - Long wait times for data base access
- **Separate processes per transaction are too costly**
- **Other techniques (e.g., message passing) are much more complex**

Example 3

- **Games have multiple active characters**
  - Independent behaviors
  - Common context or environment
- **Need "real-time" response to user**
  - For interactive gaming experience
- **Programming all characters in separate processes is really, really hard!**

- **Programming them in a single process is much harder without concurrency support.**

This problem …

- **… is partly an artifact of**
  - Unix, Linux, and Windows

    and of

  - Big, powerful processors (e.g., Core*i7*, Xeon, Ryzen)
- **… partly a consequence of history**
  - Shared computers rather than personal computers
- **… tends to occur in most large systems**
- **… ~~is infrequent in small-scale systems~~**
  - ~~PDAs, cell phones~~
  - ~~Closed systems (i.e., controlled applications)~~

Solution:– *Threads*

- **A *thread* is a particular execution of a program, function, or procedure *within the context* of a Linux or Windows process**
    - I.e., a specialization of the concept of *process*
- **A thread has its own**
    - Program counter, registers, PSW
    - Stack
- **A thread shares**
    - Address space, heap, global and static data, program code
    - Files, privileges, all other resources

with all other threads of the same process

Reading Assignment

- **OSTEP**
  - §25 – §27
- **Robert Love, *Linux Kernel Development***
  - Chapter 3 – “Process Management”

Definition:– *Thread*

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Illustration

```
void main(int argc, char** argv);
char *f(char *c, int i);
```

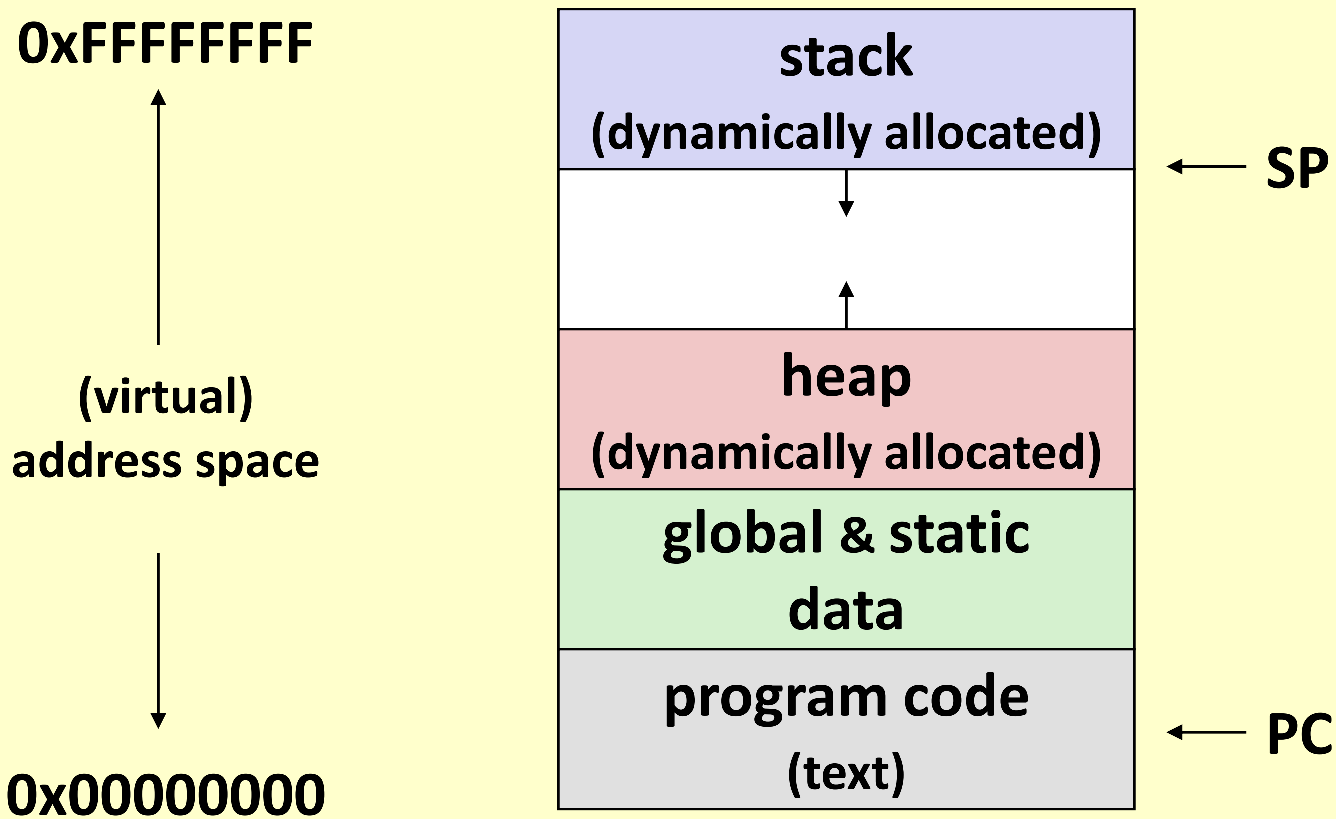
```
main(…){
  int j = …;
  char *msg = malloc(…);
  thread_t T;
  T = new_thread f(msg,j);
    …
  while (…) {
    /* loop doing something
       else */
  }
  …

  char *result = join T;
}
```

```
f(…){
  char *d = malloc(…);
  for (i=0;i<j;i++){
      …
      d[i] = c[i];
  }
  return d;
}
```

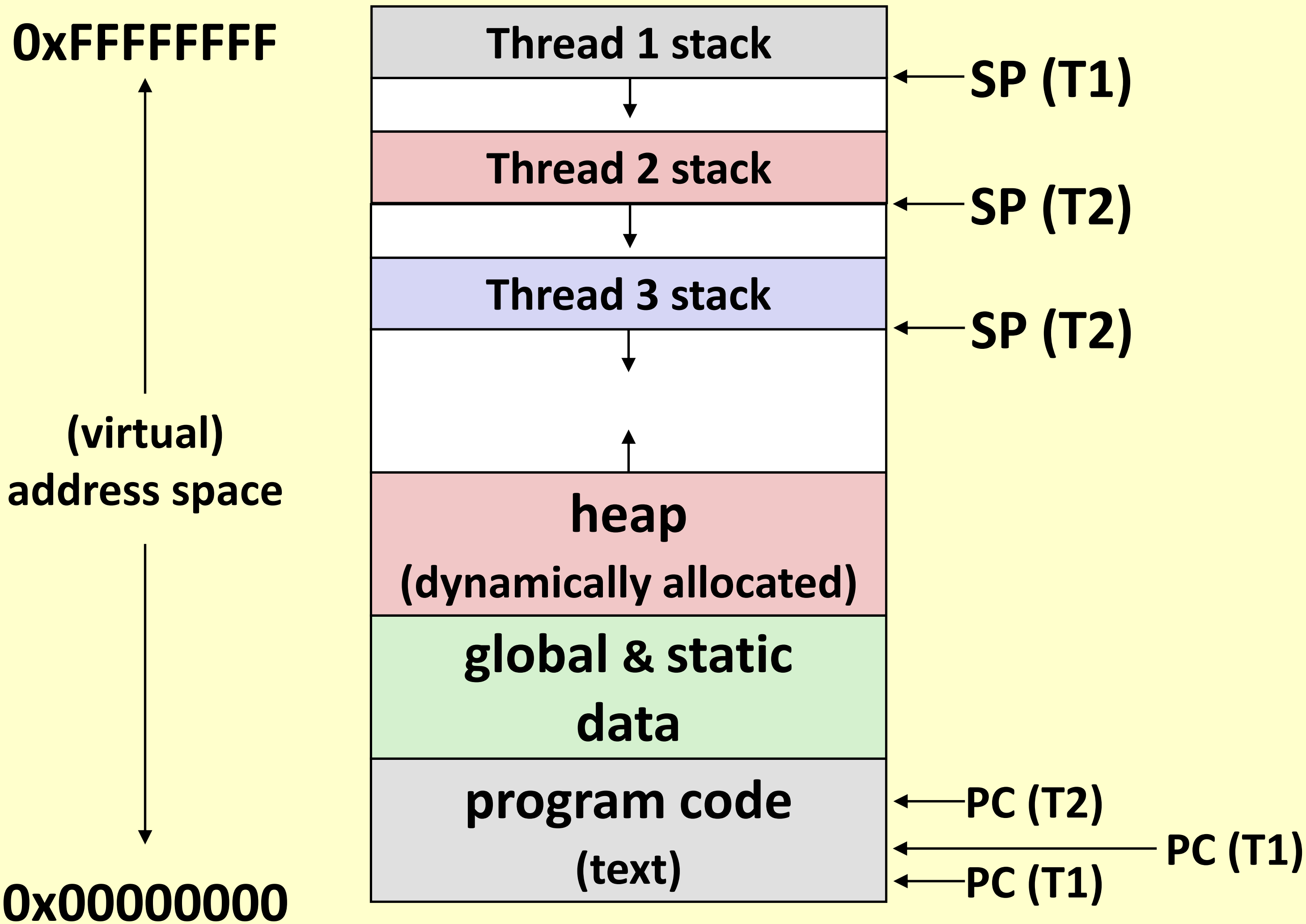
Same heap

From previous lesson

Process Address Space (traditional Linux)



Address Space for Multiple Threads



Basic Thread Functions

- ***Create* a thread**
  - Make a function call that executes *concurrently* with caller
- ***Exit* a thread**
  - *I.e.,* thread terminates or returns from its function
- ***Join* a thread**
  - Wait until the designated thread terminates, capture its return value, delete its stack
- **…**

Basic Thread Functions (continued)

- …
- ***Detach* a thread**
  - *S*eparate it from its creators
  - Becomes a standalone, independent execution
  - Not "*joinable*"; no value returned
  - Stack goes away upon termination
- ***Get own thread ID***
  - *I.e.,* get the number of my own thread
- …

Another Example

```
// web server

while (true) {
   listen for web request
   allocate private socket
   create & detach new
     thread to serve
     request
   …
}
```

```
// individual request
// handler

interpret request
while (!done) {
   interact with client
     over private socket
   …
}
exit thread
```

Benefits

- Responsiveness
- Resource Sharing
- Economy
- Better utilization of multi-processor architectures than is achievable with just processes

Using Threads

- **Everyone uses threads nowadays**
  - Many purposes
  - Many languages

- **Programming applications with concurrent activity within them has become an essential skill**
  - I.e., some form of threads

Questions?

Tools for using Threads

- **Three primary thread libraries: –**
  - POSIX *pthreads*
  - Win32 threads
  - Java threads

  - Python
  - Others?

See the man pages for these functions

Thread Interface

- E.g., POSIX pthreads API:
  - `int pthread_create(pthread_t *thread, const pthread_attr_t *attr, void*(*start_routine)(void), void *arg)`
    - creates a new thread of control
    - new thread begins executing the function `start_routine(arg)`
  - `pthread_exit(void *value_ptr)`
    - terminates the calling thread
  - `pthread_join(pthread_t thread, void **value_ptr)`
    - blocks the calling thread until the specified thread terminates
  - `pthread_t pthread_self()`
    - Returns the calling thread's identifier

Project 3 will use `pthreads`

Implementing Threads

- **In *User space***
  - User-space function library
  - Runtime system – similar to process management except in user space
  - Windows NT – *fibers:* a user-level thread mechanism

- **In *Kernel***
  - Primitive objects known to and scheduled by kernel
  - Linux: *lightweight process* (LWP)
  - Windows NT, XP, Vista, 7, 10:– *threads*

Implementing Threads

- **In *User space***
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Obsolete

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Threads Implemented in User Space

- Thread management done by non-privileged threads library
- Runs in process address space

User-Space Threads (continued)

- **Can be implemented without kernel support**
    - … or knowledge!
- **Program links with a runtime system that does thread management**
    - Operations are very efficient (function calls)
    - Space efficient and all in user space (TCB)
    - Task switching is very fast
- **Since kernel not aware of threads, there can be scheduling inefficiencies or issues**
    - E.g., blocking I/O calls
    - Non-concurrency of threads on multiple processors

User-Space Threads

- Obsolete because all modern kernels support threads at kernel level
- Still (somewhat of) a performance issue
- Research focused on how to avoid system calls for thread synchronization, creation, deletion, etc.

Questions?

Threads Implemented in Kernel

- **Supported by the Kernel**
  - OS maintains data structures for thread state and does all of the work of thread implementation.
- **Examples**
  - Windows XP/2000/Vista/7/10
  - Solaris
  - Linux version 2.6, etc.
  - Tru64 UNIX
  - Mac OS X
  - …

Kernel-level Threads (continued)

- **OS schedules *threads* instead of *processes***
- **Benefits**
  - Overlap I/O and computing in a process
  - Creation is cheaper than processes
  - Context switch *can* be faster than processes
- **Negatives**
  - System calls needed for thread operations
    - High overhead
  - Additional OS data space for each thread

Threads Supported by Processor

- **E.g., Intel Hyperthreading™**
  - www.intel.com/products/ht/hyperthreading_more.htm
- **Multiple processor cores on a single chip**
  - True concurrent execution within a single process
- **Requires kernel support**
- **Exposes many issues**
  - Critical section management of synchronization primitives at kernel level
  - Multiple threads scheduling from same ready queue
  - Multiple interrupts in progress at one time

Unix Processes *vs.* Threads

- **On a 700 Mhz Pentium running Linux**
  - Processes:
    - **`fork()`** / **`exit()`**: 250 microsec
  - Kernel threads:
    - **`pthread_create()`/`pthread_join()`**: 90 microsec
  - User-level threads:
    - **`pthread_create()`/`pthread_join()`**: 5 microsec

Some Issues Pertaining to Threads

- **Process global variables**
  - E.g., `ERRNO` in Unix — a global variable set by system calls
- **Semantics of `fork()` and `exec()` system calls for processes**
- **Thread cancellation**
- **Signal handling**
- **Thread pools**
- **Thread specific data**
- **Scheduler activations**

Semantics of `fork()` and `exec()`

- **Does `fork()` duplicate only the calling thread or all threads?**
  - Easy if user-level threads
    - All threads are duplicated, unbeknownst to kernel
  - Not so easy with kernel-level threads
    - Linux has special **`clone()`** operation
      - Creates new thread in current address space
      - Specifies function to run
      - See **`man`** page
    - Windows XP/Vista/7/10 has something similar

Thread Cancellation

- **Terminating a thread before it has finished**
- **Two general approaches:**
  - *Asynchronous cancellation* terminates the target thread immediately
  - *Deferred cancellation* allows the target thread to periodically check if it should be cancelled

Modern Linux Threads

- **Implemented in kernel**
- **“A thread is just a special kind of process.”**
  - Robert Love, *Linux Kernel Development,* p.23
- ***The* primary unit of scheduling and computation implemented by Linux 2.6 (and later) kernel**
- **Every thread has its own `task_struct` in kernel**
- **…**

Modern Linux Threads (continued)

- *Process* `task_struct` has pointers to own memory & resources
- *Thread* `task_struct` has pointer to process's memory & resources

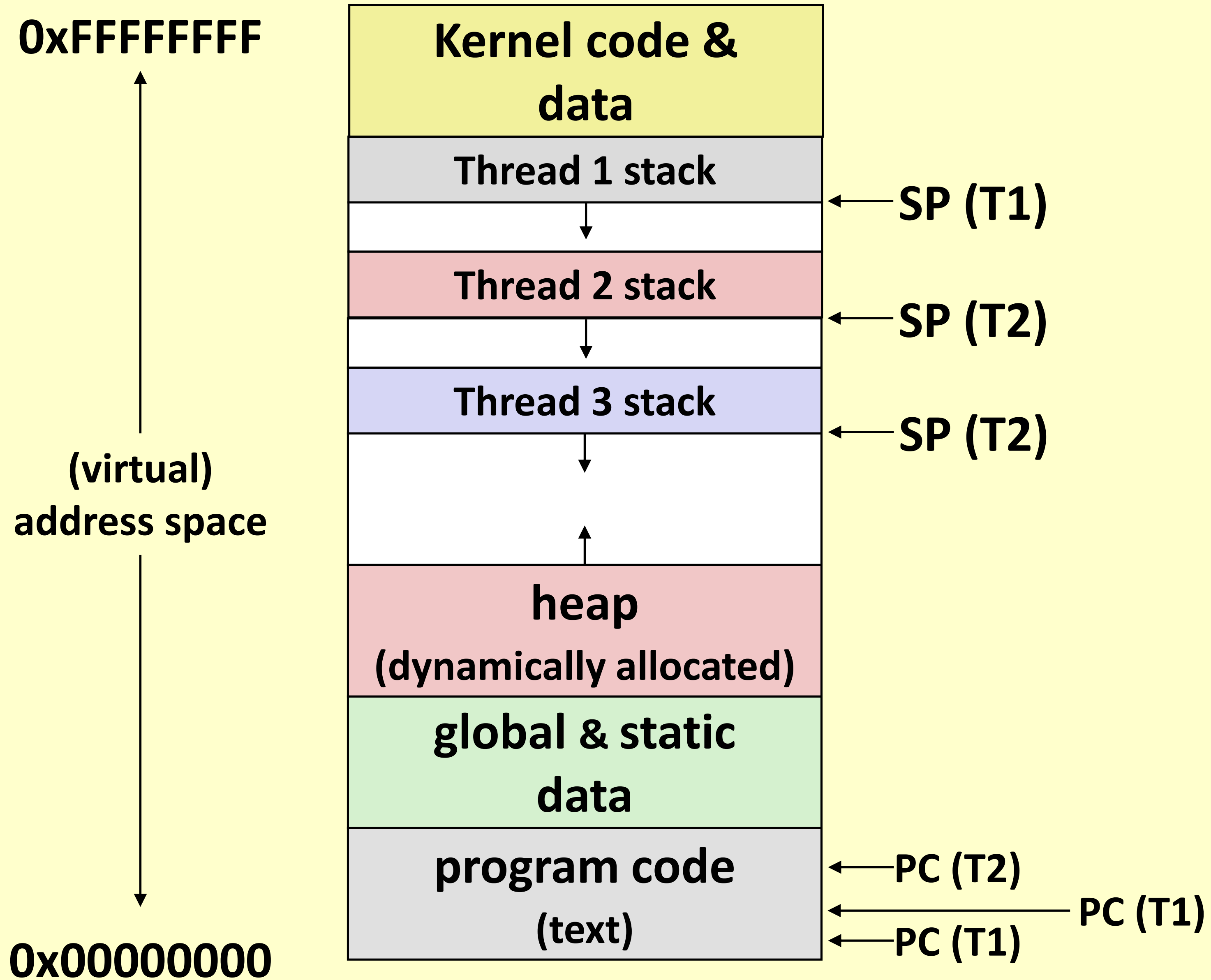
- `fork()` and `thread_create()` are library functions implemented by `clone()` kernel call
- …

Modern Linux Threads (continued)

- **Threads are scheduled independently of each other**
- **Threads can block independently of each other**
  - Even threads of same process
- **Threads can make their own kernel calls**
  - Kernel maintains a small *kernel stack* per thread
  - During kernel call, kernel is in *process context* (next slides)

Digression – Process Address Space

- **Linux includes (parts of) *kernel* in every address space**
    - Protected
    - Easy to access
    - Allows *kernel* to see into client processes
        - Transferring data
        - Examining state
        - …
- **Also many other operating systems**


0xFFFFFFFF
(virtual)
address space
0x00000000
Kernel code & data
Thread 1 stack
Thread 2 stack
Thread 3 stack
heap
(dynamically allocated)
global & static data
program code
(text)
SP (T1)
SP (T2)
SP (T2)
PC (T2)
PC (T1)
PC (T1)

Linux Kernel Implementation

- **Kernel may execute in either *Process context* vs. *Interrupt context***
- **In *Process context*, kernel has access to**
  - Virtual memory, files, other process resources (of one process)
  - May sleep, take page faults, etc., on behalf of process
- **In *Interrupt context*, no assumption about what process was executing (if any)**
  - No access to virtual memory, files, resources
  - May not sleep, take page faults, etc.

Modern Linux Threads (continued)

- **Multiple threads can be executing *in kernel* at same time**
- **When in *process context*, kernel can**
    - sleep on behalf of its thread
    - take pages faults on behalf of its thread
    - move data between kernel and process or thread
    - …

Implications of Threads in Kernel

- Kernel maintains a small stack for ***each*** thread in kernel space
- Large enough for *one* system call
  - 4 kBytes (32 bit architectures)
  - 8 kBytes (64-bit architectures)
- Limit on total number of threads supportable by kernel

Bound on number of function calls within system call

Threads in Linux Kernel

- **Kernel has its own threads**
  - No associated *process context*
- **Supports concurrent activity within kernel**
  - Multiple devices operating at one time
  - Multiple application activities at one time
  - Multiple processors in kernel at one time
- **A useful tool**
  - Special kernel thread packages, synchronization primitives, etc.
  - Useful for complex OS environments

Windows NT/XP/Vista Threads

- **Much like Linux 2.6 threads**
  - Primitive unit of scheduling defined by kernel
  - Threads can block independently of each other
  - Threads can make kernel calls
  - …
- **Process**
  - A higher level (non-kernel) abstraction
  - A *container*

Threads – Summary

- **Threads were invented to counteract the heavyweight nature of *Processes* in Unix, Windows, etc.**

- **Provide lightweight concurrency *within* a single address space**

- **Have evolved to become *the* primitive abstraction defined by kernel**
    - Fundamental unit of scheduling in Linux, Windows, etc

Reading Assignment

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Questions?