System Architecture

5 Threads

Thread Model, Implementation

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Agenda

- Motivation
- Thread Models
- Thread Types
- Problems with Threads
- Controlling Threads
- Implementing Threads (TCB)

Motivation

Single-Threaded Example

- Imagine the following C program:

```
main() {
    ComputePI(“pi.txt”);
    PrintClassList(“clist.txt”);
}
```

- *What behavior?*

Multithreaded Example

- Version of previous program with(out) Threads:

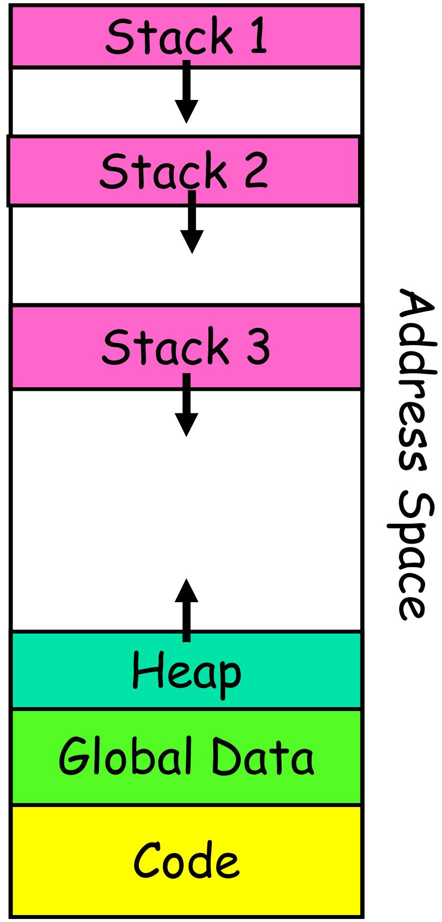
```
main() {
                 (ComputePI(“pi.txt”));
                 (PrintClassList(“clist.txt”));
}
```

- *What does “*`CreateThread`*” do?*
  - Start an independent thread running the function `ComputePI(“pi.txt”)`
  - Start an independent thread running the function `PrintClassList(“clist.txt”)`

- *How many threads? What behavior?*

Memory Footprint of Example

- If we stopped this program and examined it with a debugger, we would see
  - Three sets of CPU registers
  - Three sets of Stacks
- Problems:
  - *How to position stacks?*
  - *Maximum size of stacks?*
  - *How to handle stack overflow?*



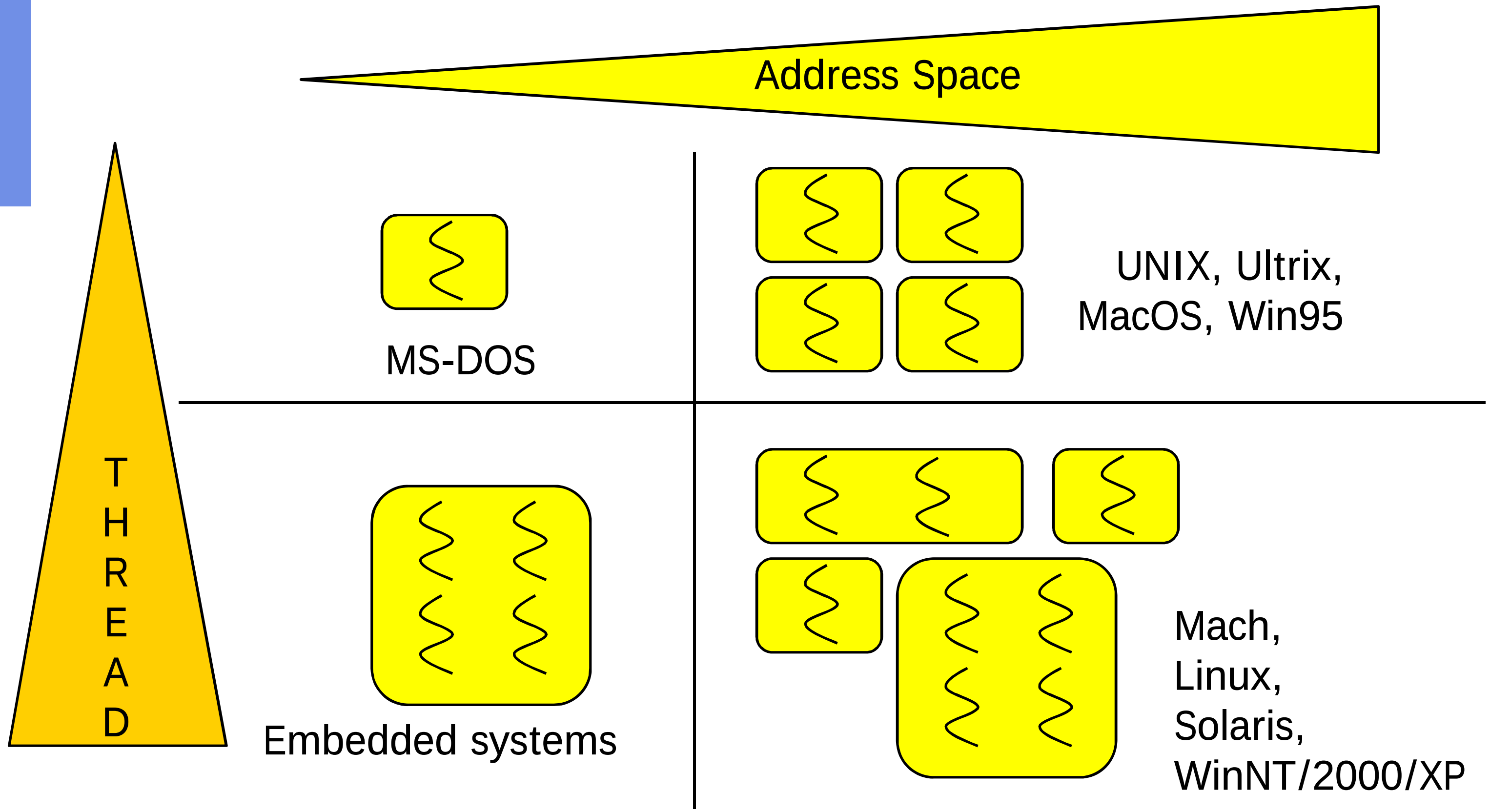
POSIX Threads Standard C/C++

```
#include <pthread.h>
#include <stdio.h>
void * run (void * d) {
  int q = *((int *) d);
  int v = 0;
  for (int i = 0; i < q; i++) { v = v +
   expensiveComputation(i); }
  return (void *) v;
}
main() {
  pthread_t t1, t2;
  int r1, r2;
  pthread_create (&t1, NULL, run);
  pthread_create (&t2, NULL, run);
  pthread_wait (&t1, (void *) &r1);
  pthread_wait (&t2, (void *) &r2);
  printf ("r1 = %d, r2 = %d\n", r1, r2);
}
```

Example: JAVA Threads

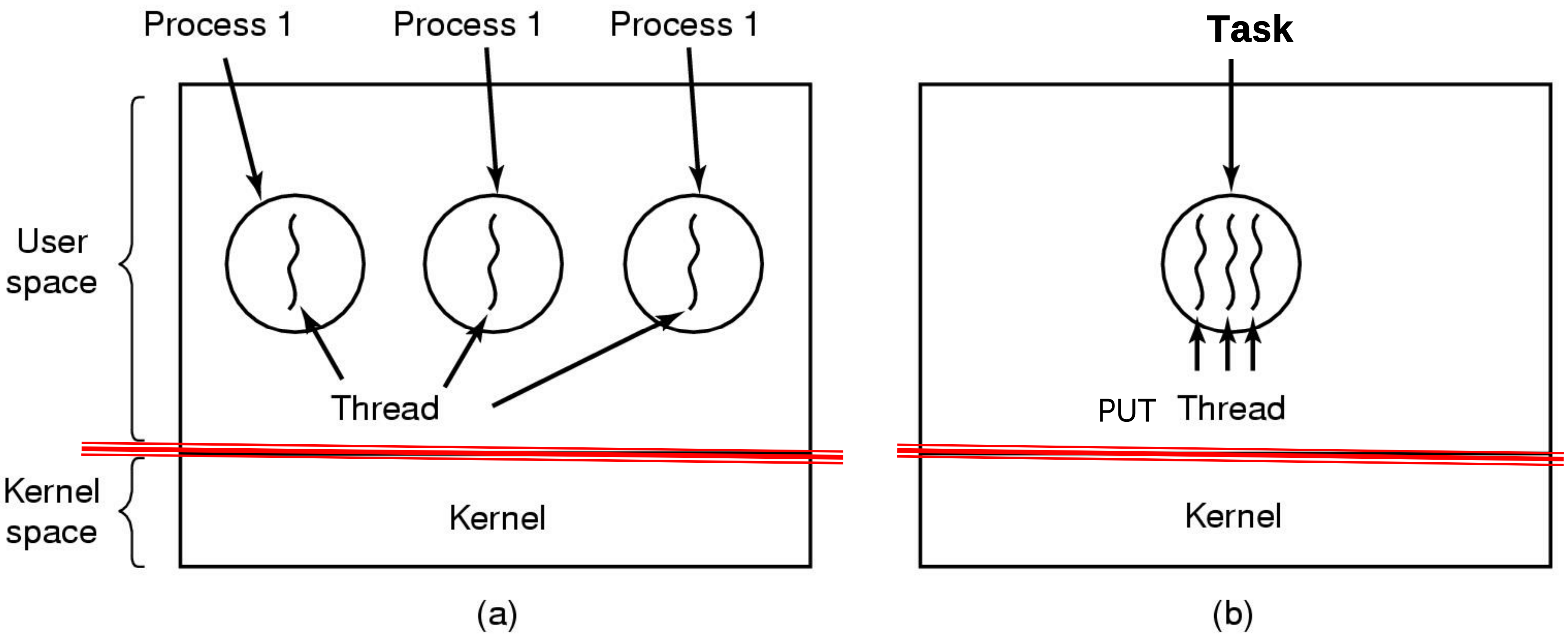
```
import java.lang.*;
class Worker extends Thread implements Runnable {
  public Worker (int q) { this.q = q; this.v = 0; }
  public void run() {
    int i;
    for (i = 0; i < q; i++) { v = v + i; }
  }
  public int v;
  private int q;
}
public class Example {
  public static void main(String args[]) {
    Worker t1 = new Worker (100);
    Worker t2 = new Worker (100);
    try {
      t1.start();
      t2.start();
      t1.join();
      t2.join();
    } catch (InterruptedException e) {}
    System.out.println ("r1 = " + t1.v + ", r2 = " + t2.v); }
   }
```

Classifying "Threaded" Systems



- One or many address spaces
- One or many threads per AS

Processes versus Task



3 processes with 1 main thread

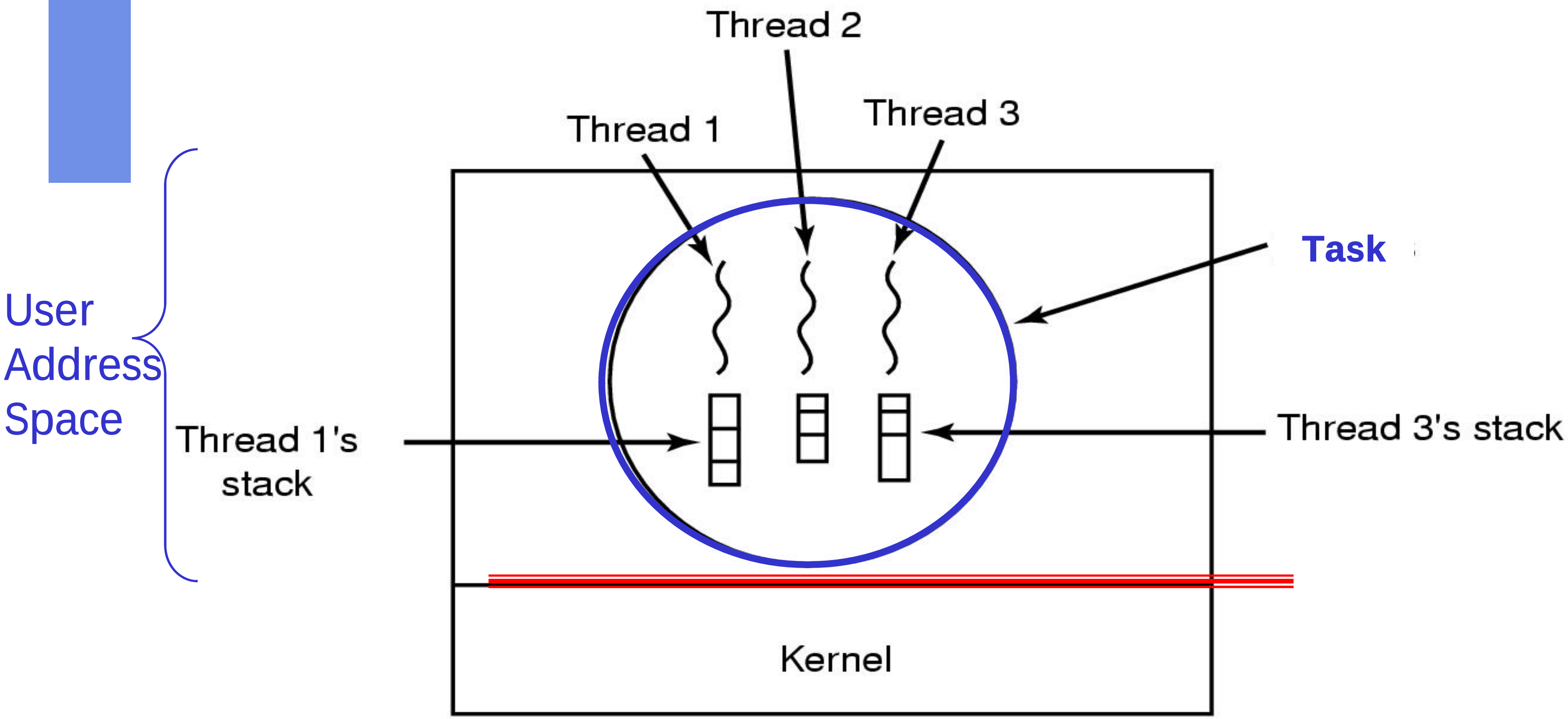
1 task with 3 threads

Potential Benefits of Threads

- Responsiveness
  - Reaction time on external or internal events
- Convenience of programming
  - Special threads for different activities
  - Install appropriate attributes for a thread
    - Access rights
    - Scheduling info
- Economy
  - Resource Sharing
  - Cheaper creation and deletion
- Better utilization of SMPs
  - Heavily depending on thread model

Thread Model

Abstract Thread Model

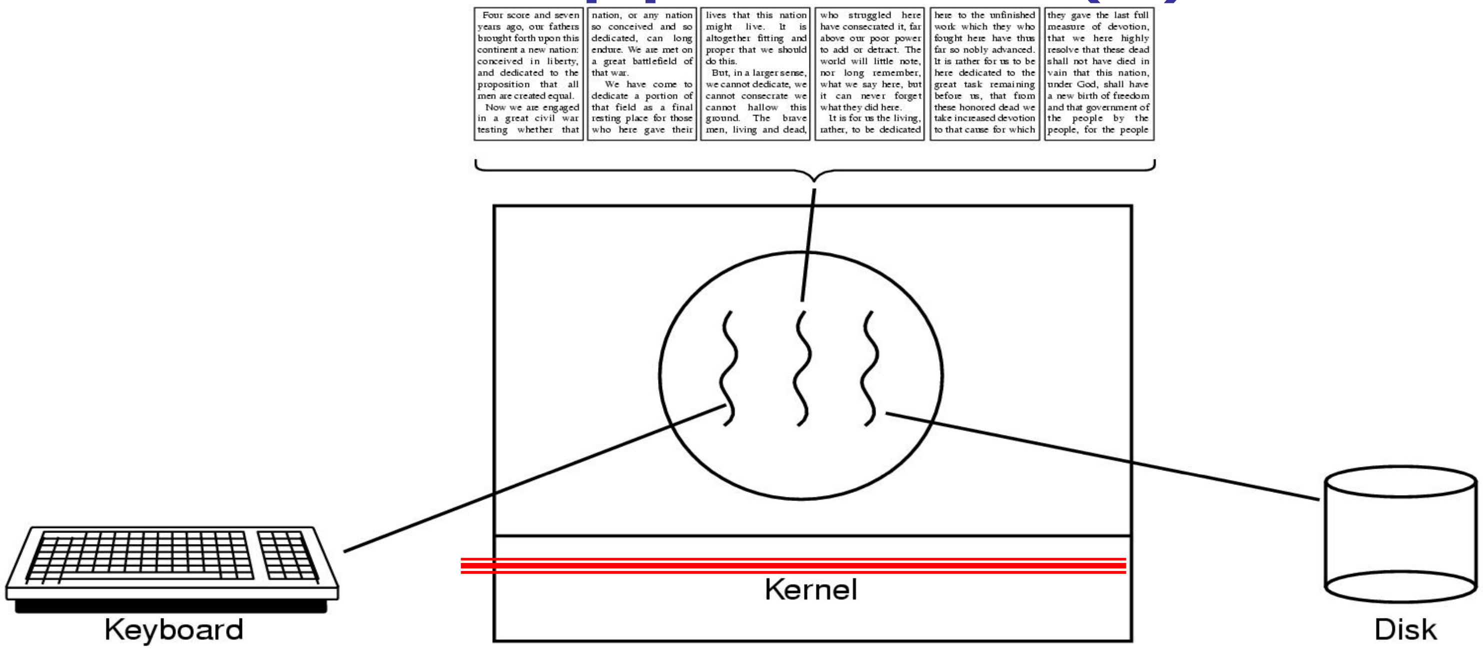


Remark: In whatever thread model,
each thread has its own user stack

Common Properties of Thread Models

- Code and data regions of a thread are always located in the user space of the surrounding task
  - Code of a thread can be located in the shared code segment of the task or in a private code segment
- A user stack is always private to its thread, i.e. no other thread of the same AS can access its contents with a usual stack operation, BUT ....
  - it can violate the others user stacks contents via pointer operations, when it can guess the stack addresses of the other user stacks
- Thread data can be part of the public data region (e.g. heap, global variables)

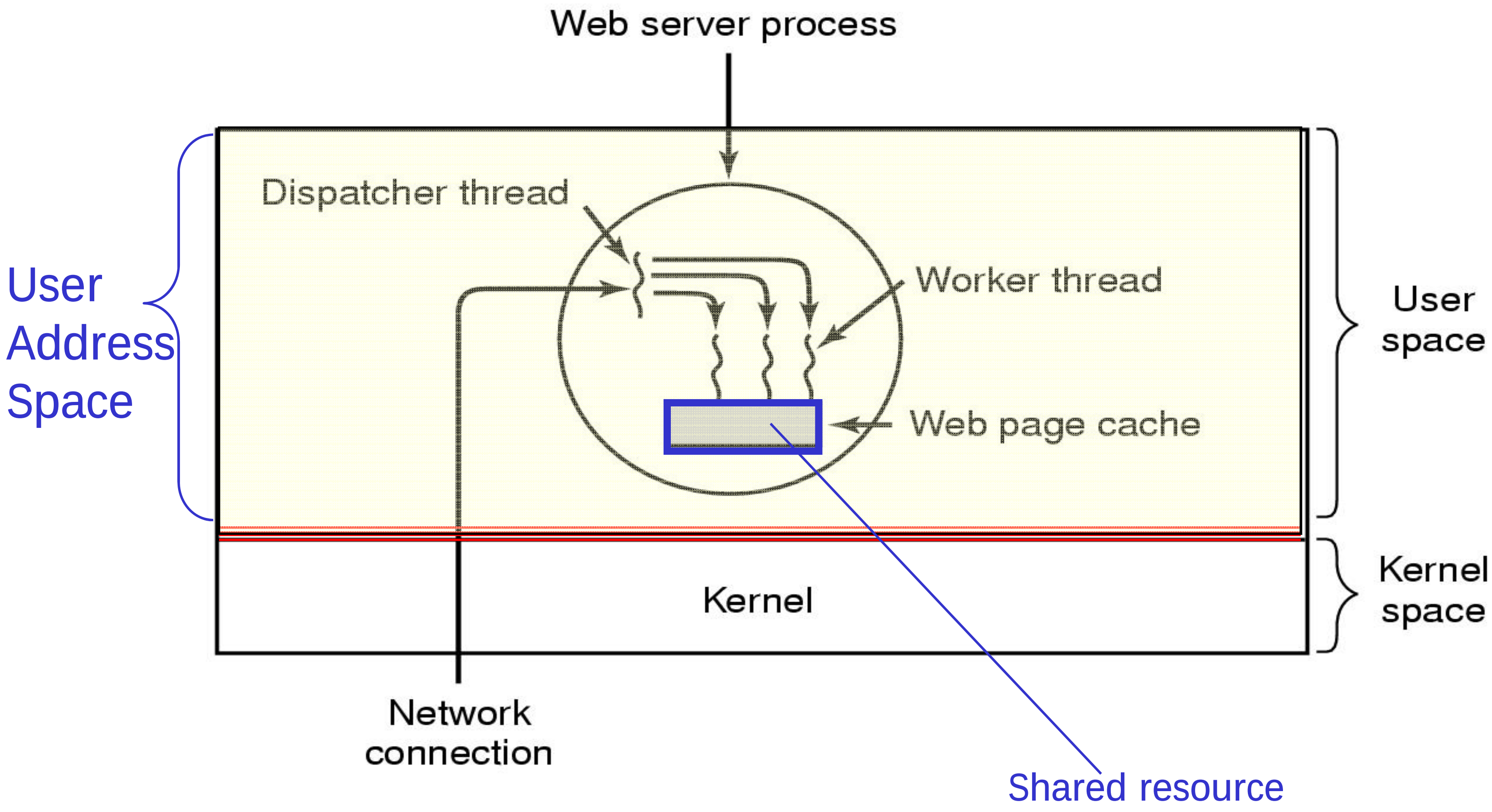
Multithreaded Application (1)



Word “processor” with three threads:

- Controlling keyboard input and updating word document
- Displaying current content
- Updating word document on the disk

Multithreaded Application (2)



A multithreaded Web server

Implementation of Threads

- **T**hread **C**ontrol **B**lock (**TCB**) contains
  - Execution Context
    - CPU registers, instruction pointer, stack pointer
    - HW specific
  - Scheduling Info
    - Scheduling State (more later), priority, estimated CPU time
    - Policy specific
  - Resource Usage Info
    - Already used CPU time
    - HW & OS specific
  - Various Pointers:
    - Implementing thread states, pointer to enclosing TaskCB
    - Implementation specific
  - ...

Task versus Thread

- Items shared by all threads of the same task in most thread models
  - Address space
  - Global variables
  - Open files
  - Children (what type of?)
  - Pending alarms
  - Signals and signal handlers
  - Accounting information

- Items private to each thread
  - Instruction pointer (“program counter”)
  - Registers, flags etc. $\Rightarrow$ context of thread
  - Stack pointer & stack (user stack, kernel stack?)
  - Thread state (external state)

Thread Models

- Pure User-Level Threads (**PULT***)
  - Known only outside the kernel (e.g. within the task, or subsystem, or runtime system), often implemented by a thread library, i.e. its TCBs are located inside user space
- "Pure" Kernel-Level Threads (**KLT***)
  - Every KLT is explicitly known to the kernel, its TCB (at least parts of it) is located inside the kernel
- Hybrid Threads (**HLT**)
  - Take advantage of both pure models

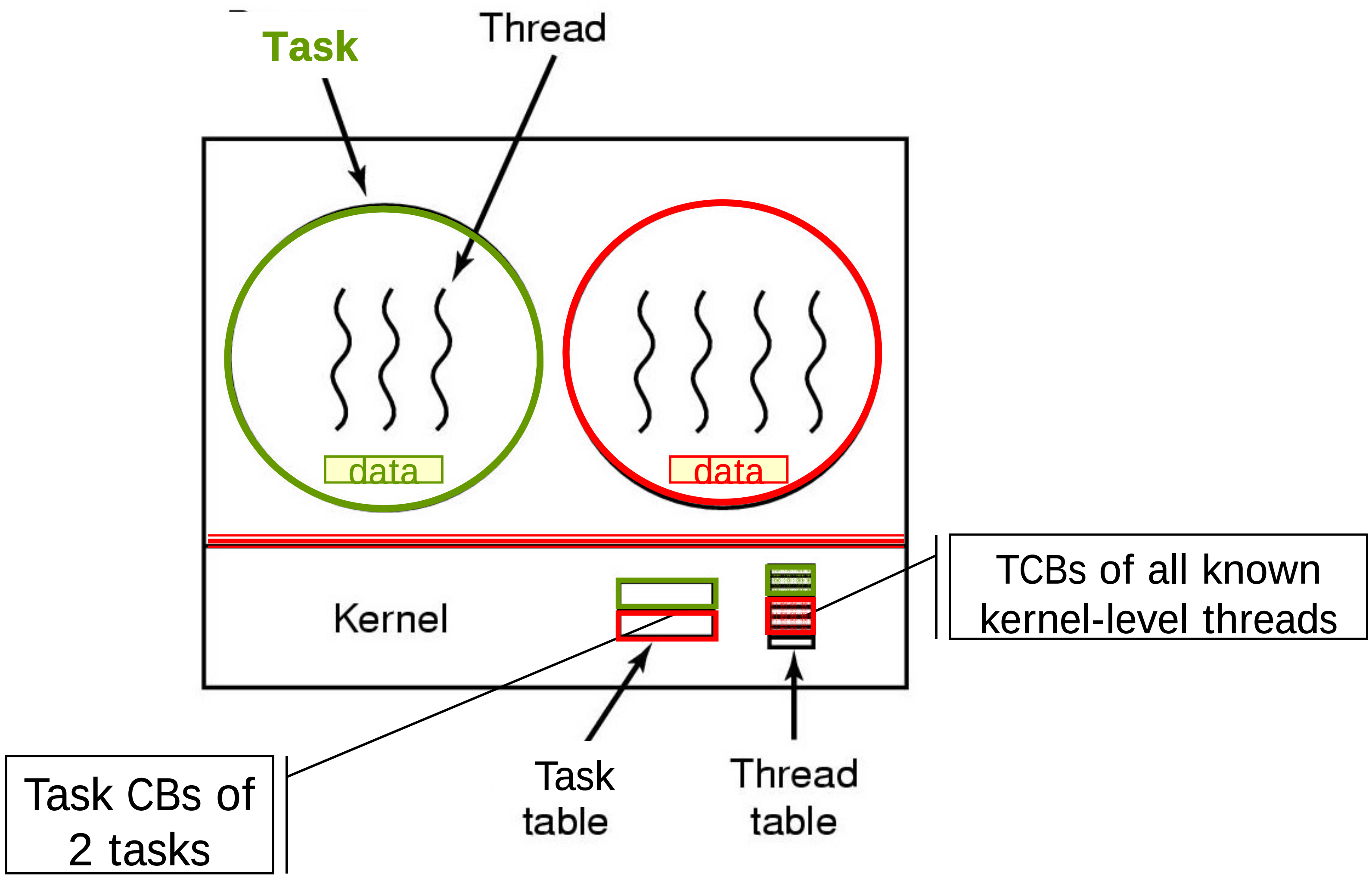
*often called user threads, user-space threads, green threads ...

*This term is KIT specific, also called native threads (or even kernel threads, which is completely misleading)

Types of Threads

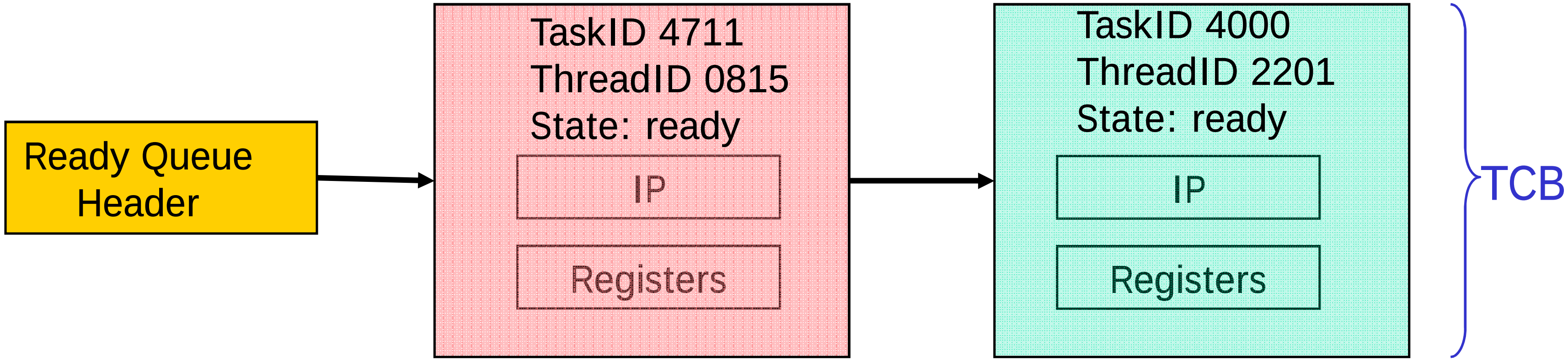
- Kernel-Level Threads (KLT)
- Pure User-Level Threads (PULT)
- Hybrid-Level Threads (HLT)
- Kernel(-Mode) Threads (KMT)
- Examples

Implementing KLTs



Management of KLTs

- Kernel knows about tasks <u>and</u> the KLTs
  - Threads of type KLT are objects of CPU scheduling
  - TaskCB contains info on shared resources, AS + set of its threads
  - TCB contains info on CPU context, state + task affiliation
  - TCB might be moved between thread states



- TCBs can be made smaller than a TaskCB, e.g.
  - Linux TaskCB has 106 fields
  - Linux TCB would only require 24 fields (**but????)**

Advantages of KLTs

- KLTs from the same task can be assigned to different CPUs on a SMP ($\Rightarrow$ real parallelism)
  - *Always a speed up?*
  - *Speed up even on a single processor?*
- A blocking system call only blocks the calling KLT (not the complete task)
- A **`thread_switch`** between 2 KLTs of the same task is faster than ~ between 2 KLTs of different tasks, because you do not need an AS-Switch with
  - Switching paging information
  - TLB flushing & restoring

Disadvantages of KLTs

- Each thread related operation requires overhead, it always needs kernel entrance/kernel exit
- Relatively high initialization costs
- All KLTs must live with the more or less flexible kernel scheduling policy
  - ∃ few systems with customizable kernel scheduling policies
- Besides the entities “process” and “task” the kernel also has to know about threads
  - Kernel is more complicated
  - More kernel space is needed for TaskCBs + TCBs

Examples Systems offering KLTs

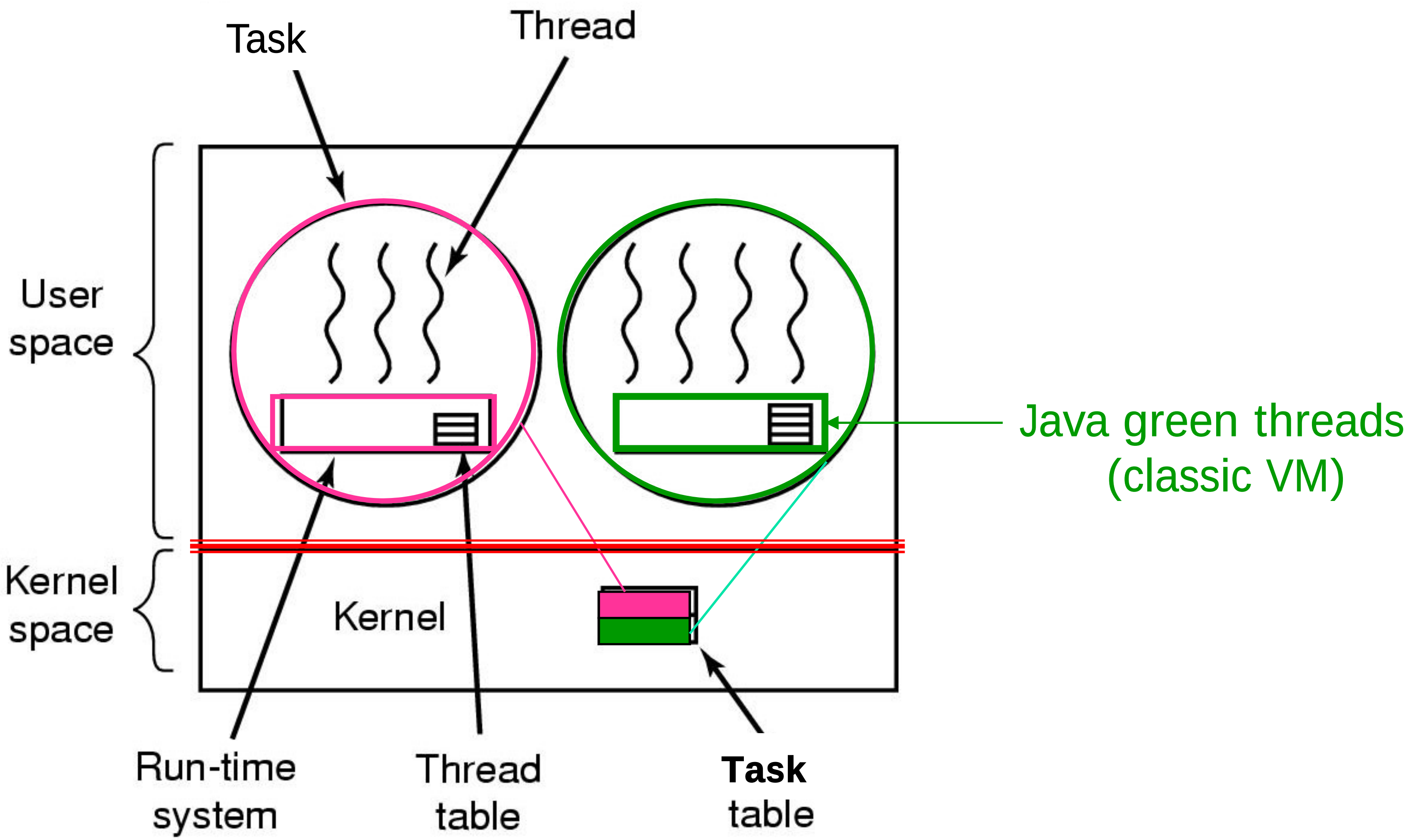
- Windows NT/XP/2000
- Solaris 9 and later versions
- Tru64 UNIX
- BeOS
- MacOS X
- Linux
  - Implements the Posix 1003.1c package
  - Using the `clone()` system call
  - To take full advantage of SMPs

When to use KLTs?

What parts of a program should or can be threaded?

- A few rules of thumb:
  - ∃ groups of lengthy or special operations, e.g.
    - painting a window
    - printing a doc
    - responding to a mouse-click
    - calculating a spreadsheet column
  - Amount of shared data is relatively small, i.e. mutually obstruction neither occurs too often nor too long
  - Preview: However, you should be prepared to worry about deadlocks and race conditions

Pure User-Level Threads



Controlling PULTs

All **PULT related operations** are done inside the thread library, i.e. in user mode land

- Advantages:
  - Fast thread manipulation, typically 10-100x faster than slipping into the kernel and back again
  - UTCB can be smaller (e.g. IP, PSW, and SP)
  - Each application might use a tailored scheduling policy for its PULTs
  - Usable in an OS that does not offer KLTS (often called native threads)

Controlling PULTs

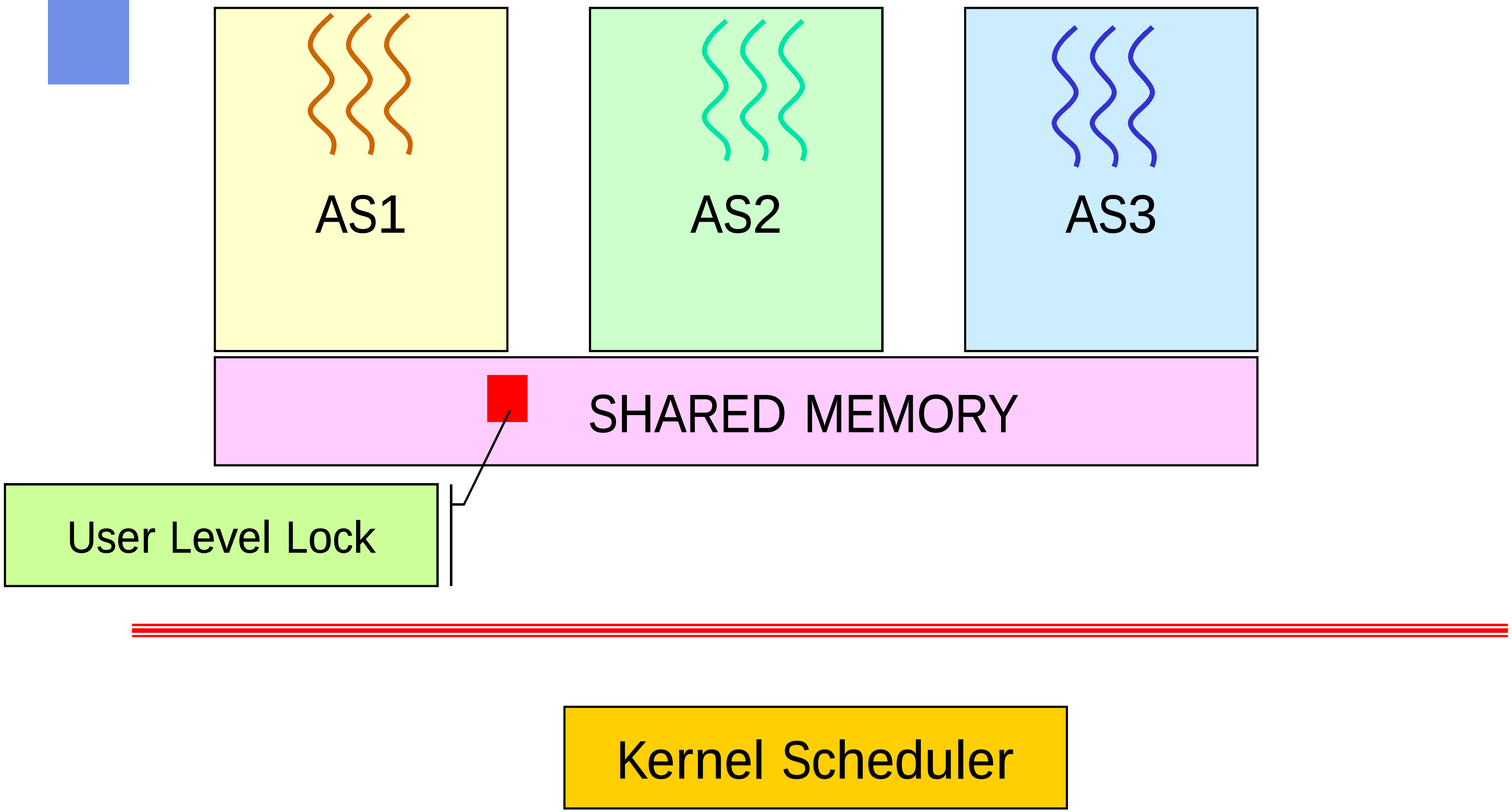
- Disadvantages:
  - Only one single PULT of a multi-threaded task can run on an SMP at any given time
  - A task always gets the same amount of the CPU independently of the number of its PULTs
  - A blocking system call (e.g. synchronous I/O) blocks the entire task, not only the calling PULT
  - Some say: Kernel might preempt a task with a PULT holding a system wide lock (thus slowing system down)

Analysis

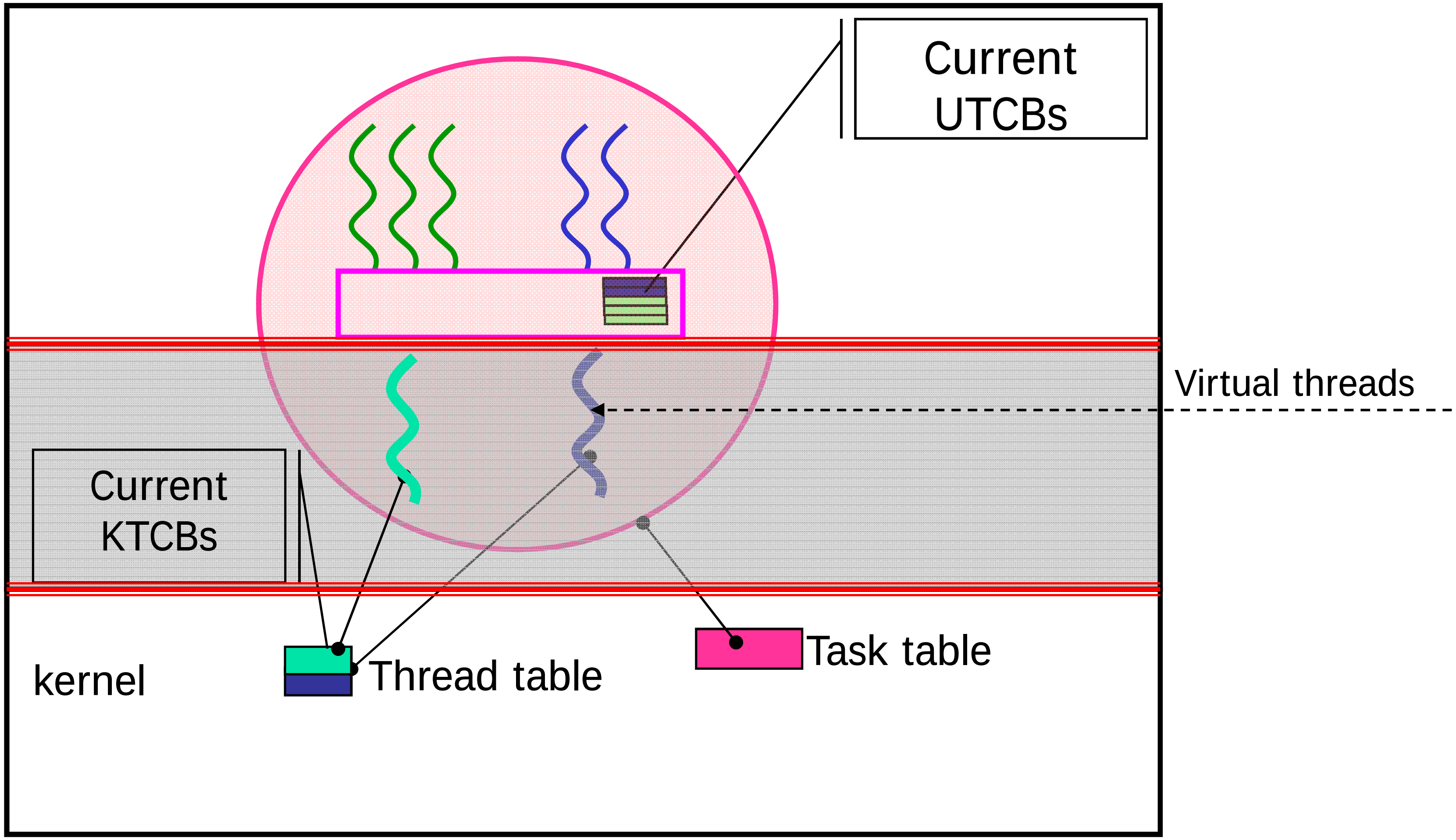
- As long as the kernel is involved in granting a lock to a PULT it can notify this fact in the related TaskCB (e.g. setting a "non preemption flag")
- Whenever the kernel wants to preempt a task, it can control whether the "non preemption flag" of the corresponding task is set
- But, assume a shared memory concept and a common lock -handled in user land- for more than 1 AS
- Then the kernel might preempt a PULT that holds a lock, some other PULTS from the related ASes are waiting for

  $\Rightarrow$ increased latency

CROSS-AS-LOCK at User Level

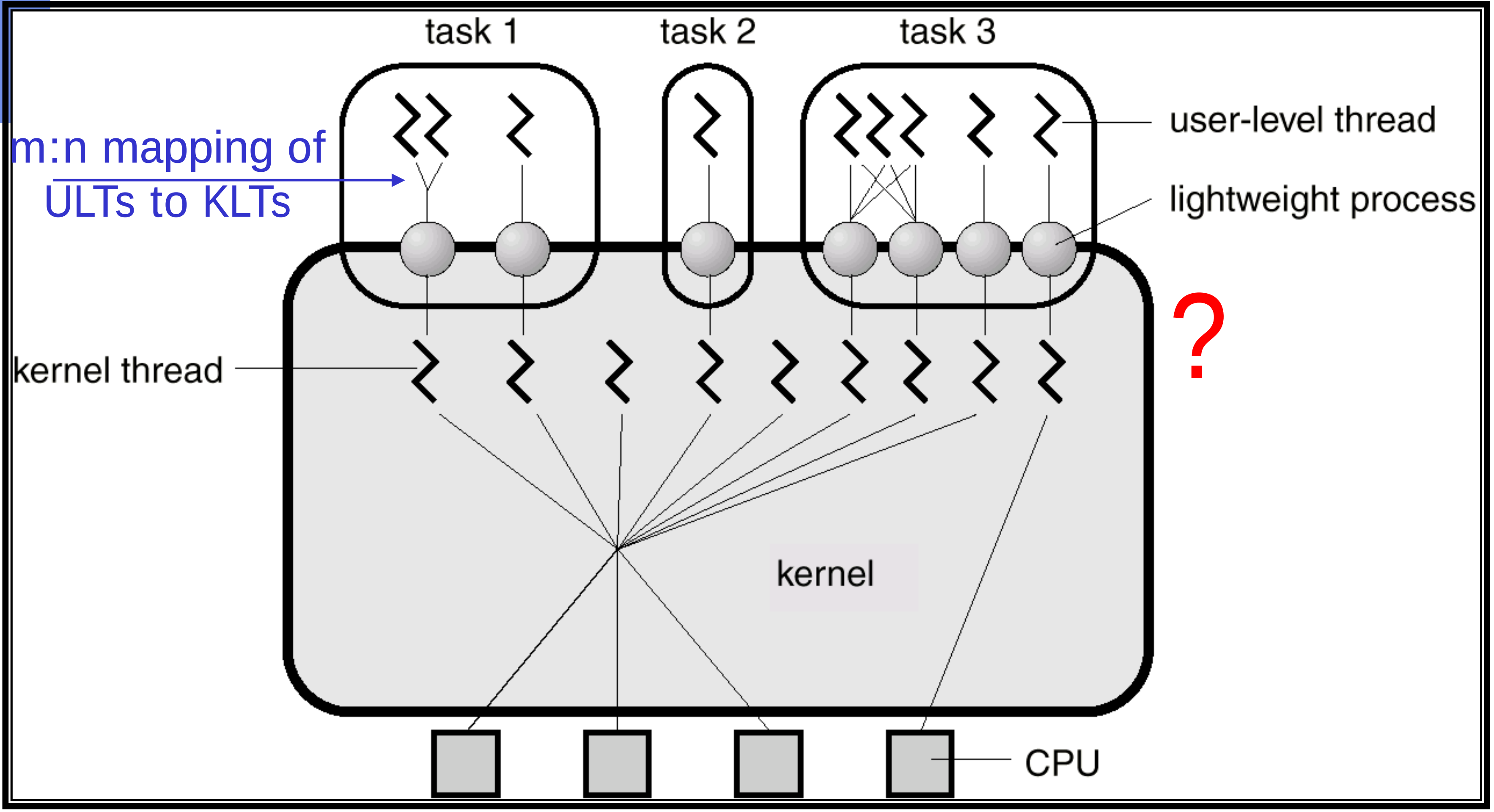


Hybrid Threads



Map user-level threads to “kernel-level threads”

Example: Solaris 2 Threads



Cons of Hybrid Thread Model*

- OS must offer native threads
- 2 scheduling layers
  - The “KLT part” of the application is managed by the kernel
  - The user-level part is managed by a scheduler in the library
  - Kernel scheduler and library scheduler have to cooperate
- Problem:
  Fundamental reliance on kernel (lower layer) calling procedures in user space (higher layer) via so called “UPCALLS”, violating the principle of layered systems

*see Anderson et al: “Scheduler Activations: Effective Kernel Support for the User-Level Management of Parallelism”, ACM, Trans. on Computer Systems, Feb. 1992

Pros of Hybrid Thread Model*

- Two ways to handle blocking system calls

  1. A blocking system call in the user-level thread only blocks its counterpart in the kernel

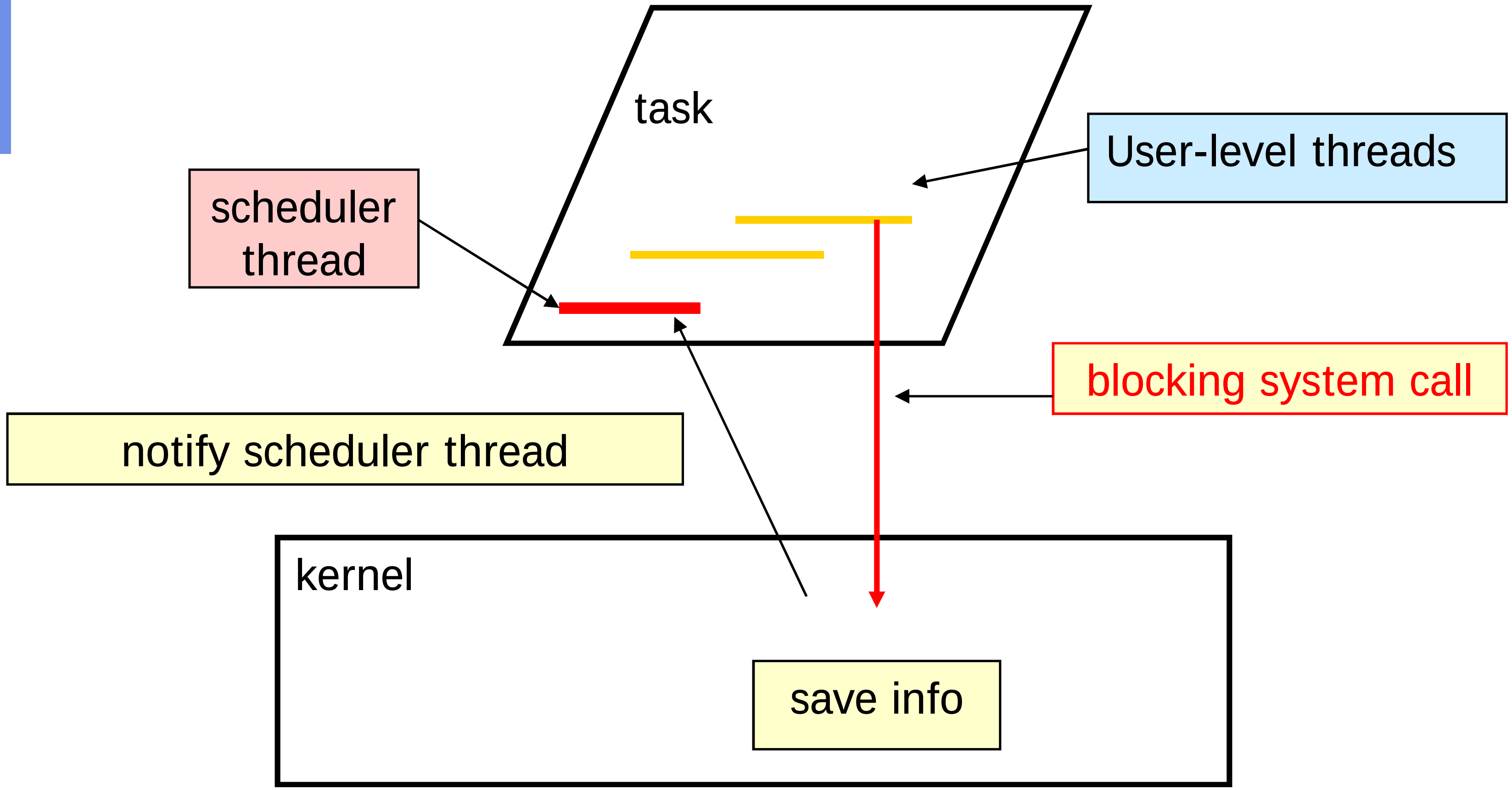
     - Only those user-level threads are blocked which are mapped to this blocked KLT

     - When the blocking criteria no longer holds, the kernel will unblock the related KLT as usual

Pros of Hybrid Thread Model*

2. Kernel blocks current KLT temporarily, recording the relevant blocking criteria in the kernel
   - But instead of **blocking the KLT for a while**, it returns control to the user-level scheduler (via a scheduler activation)
   - This user-level scheduler blocks the responsible ULT and can switch to another **ready ULT** which has been planned for this KLT
   - When the blocking situation no longer holds, the kernel informs the corresponding user-level-scheduler, which then can unblock the related user-level thread and can put it to the ready list for its KLT

Hybrid Thread Blocking

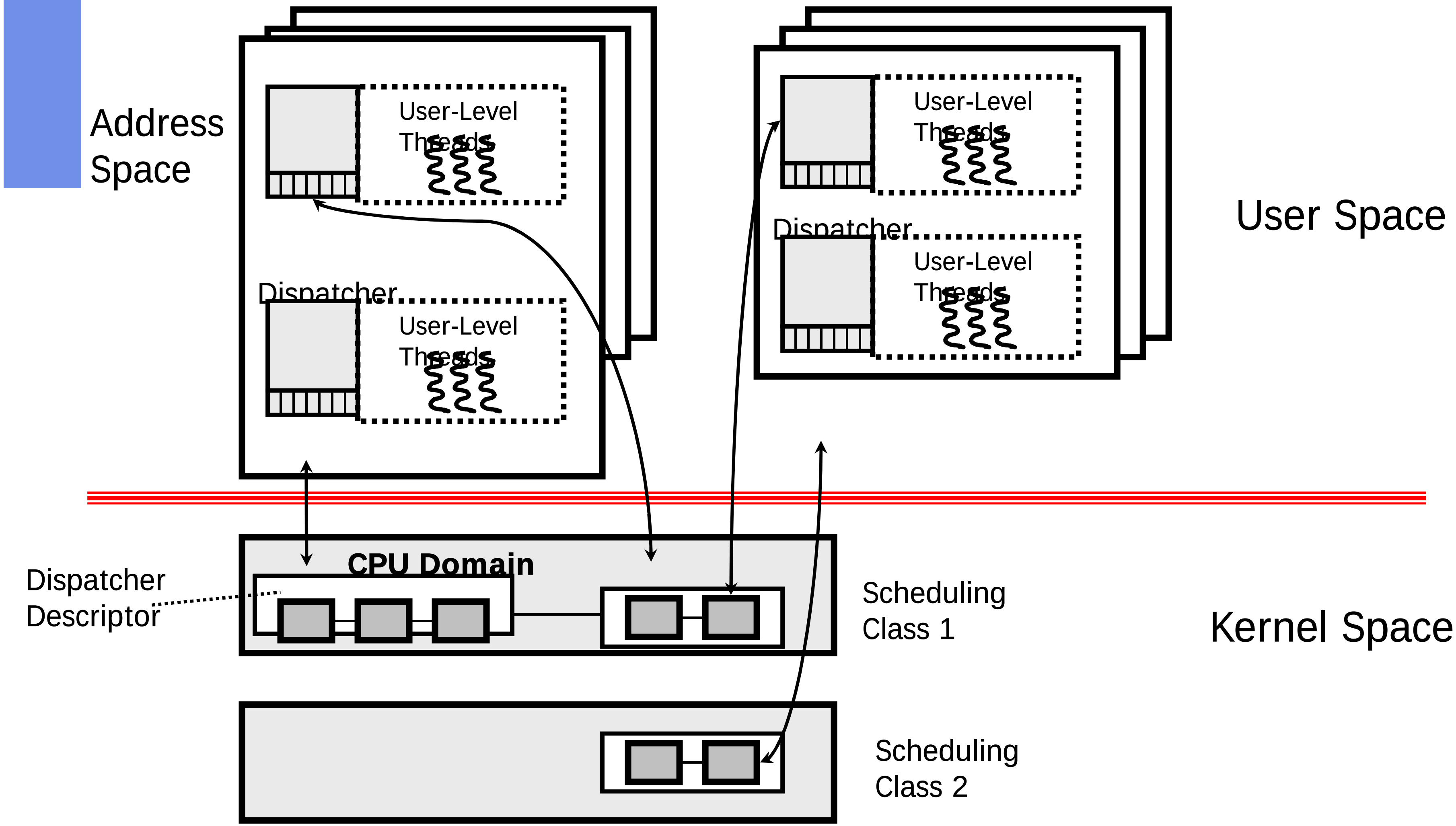


One way to handle the above situation are scheduler activations (see: Anderson et al)

PThreads

- POSIX standard (IEEE 1003.1c) API for thread creation and synchronization.
- API specifies behavior of the thread library; implementation is up to the developer of the library.
- Common in UNIX operating systems.

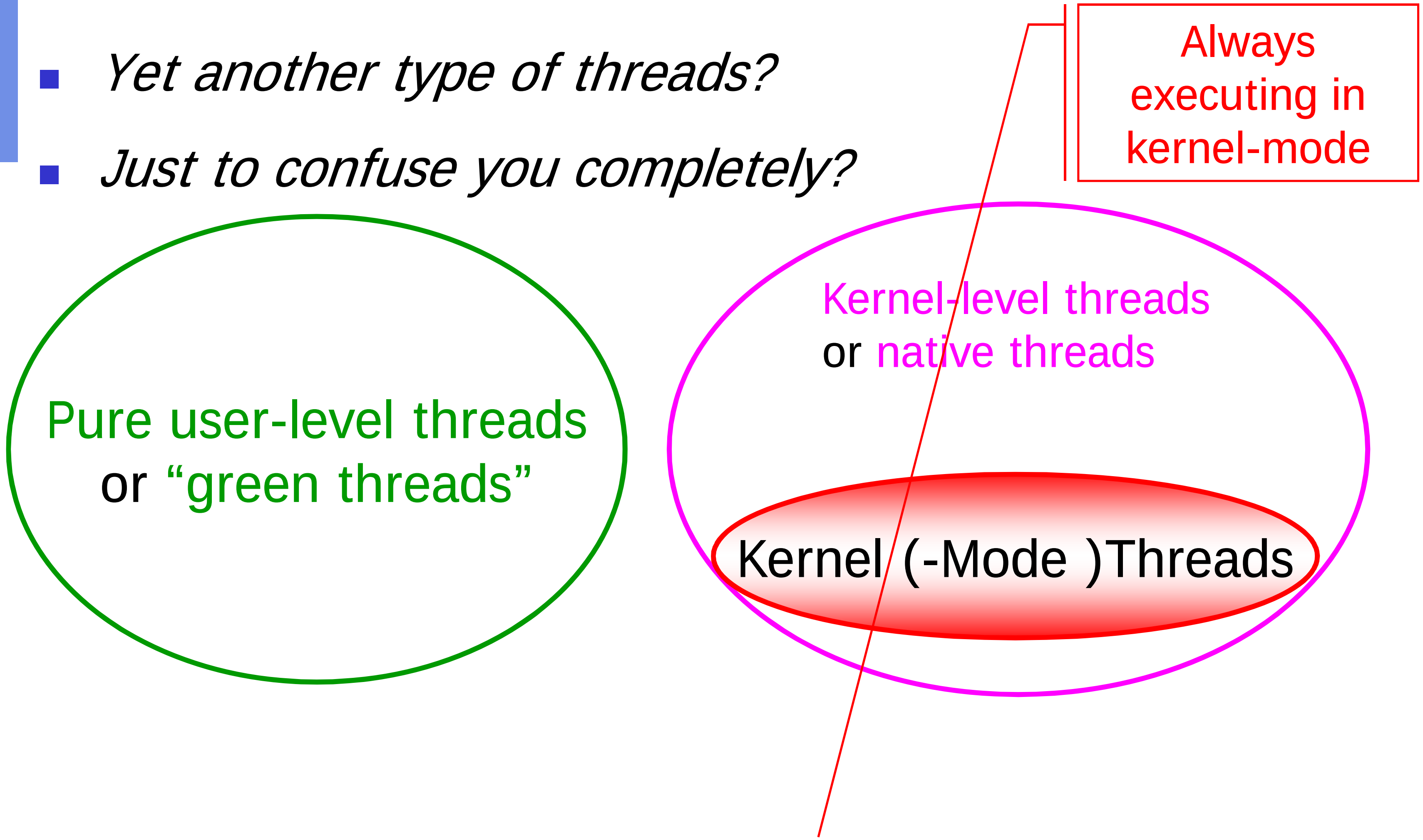
K42 Hybrid Threads[1]



[1]read the white papers: http://www.research.ibm.com/K42/

Kernel (-Mode) Threads (KMT)

- *Yet another type of threads?*
- *Just to confuse you completely?*



Kernel-Mode Threads

- Already in early Unix versions ∃ some kernel “processes” (daemons, e.g. the swapper completely mapped to KAS) and always running in kernel-mode
- **`root`** = owner of UNIX kernel processes
- Modern OS may use kernel-mode threads
- Additional problems:
  - *How (when)to schedule kernel-mode threads?*
  - *How to interact with kernel-mode threads?*
  - *How to protect sensitive kernel data from misbehaving kernel-mode threads?*

Thread Programming

Concurrent Programming

Examples of Problems

Common Problems

Why to study Thread Programming?

- Concurrent correct application programs are not yet very widespread
- Some of them have been(still are) *error-prone*[1,2] ⇒
- Skill of concurrent programming has to be trained
- Famous Mars Pathfinder problem
  - Problems with the correct synchronization of three concurrent processes

[1]For further software horror stories see:
http://www.cs.tau.ac.il/~nachumd/horror.html

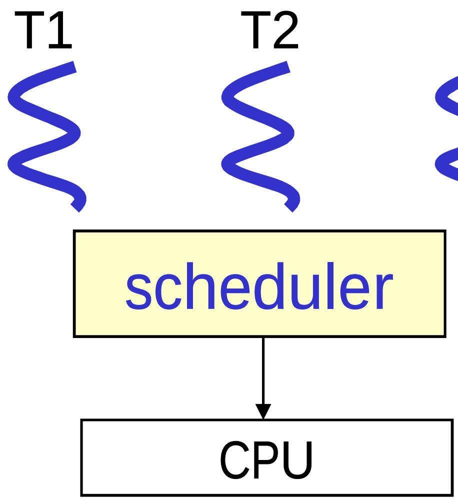
[2]http://courses.cs.vt.edu/~cs3604/lib/Therac_25/Therac_1.html

What can go wrong with Threads?

- Safety hazards
  - Program does the wrong thing due to race conditions
- Liveliness hazards
  - Program never does the right thing (live lock, deadlock)
- Performance hazards
  - Program is too slow due to excessive synchronization

Preview: Thread Scheduling

- Scheduler decides when to run a “ready” thread



Potential execution sequence

<T1, T2, T3, T1, ...>

- Programs should make no assumption about the scheduler
  - Scheduler is a “black box”

Threads Safety

- A program is thread safe if it behaves correctly when accessed from multiple threads, regardless of the scheduling or interleaving of those threads
- Race condition: program’s output is different depending on scheduler’s interleaving
  - Such a behavior is a program bug
- Study the following program example on your own

```
public class ThreadTest extends Thread {
    private static int x =1;
    public void run() {
      x++;
    }

   public static void main(String[] args){
     thread t1 = new ThreadTest();
     thread t2 = new ThreadTest();
     t1.start();
     t2.start();
     try {
       t1.join; // wait for t1 to finish
       t2.join; // wait for t2 to finish
     }
     catch(InterruüptedException iex) {}
     printf(“Value of x == %d“, x);
 }

}
```

Safety Hazard: `x++`

- Key point: x++ is not an atomic instruction, but consist of multiple CPU instructions, e.g.
  - Load x from memory
  - Increment x
  - Store x to memory
- In MIPS assembly this could mean:

```
LW St, offset($s)
ADDI $t,$t,1
SW $t, offset($s)
```

Unsafe Thread Schedule

- Given threads t1 and t2:

Thread switch

Thread switch

```
LW $t, offset($s)        //for t1
LW $t, offset($s)        //for t2
ADDI $t,$t,1             //for t2
SW $t, offset($s)        //for t2
ADDI $t,$t,1             //for t1
SW $t. offset($s)        //for t1
```

- Final result: Value of x == 2

Thread Cancellation

- "Killing" a thread before it has finished
- Two general approaches:
  - Asynchronous cancellation terminates the thread immediately
  - Deferred (lazy) cancellation allows the thread to periodically check if it should be cancelled, e.g. whenever control flows enters the kernel

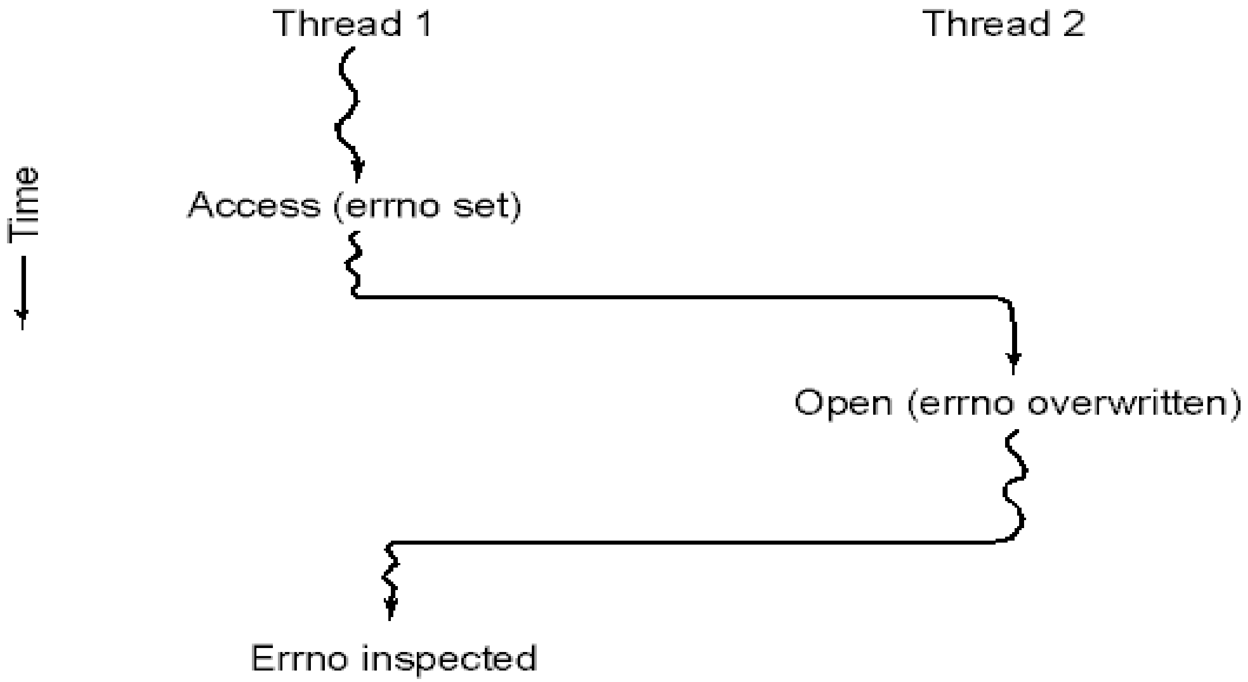
Signal Handling

- Signals are used in UNIX systems to notify a process that a particular event has occurred
- *How to signal PULTs or KLTs of a task?*
- A signal handler is used to process appropriate actions after the signal has arrived
  1. Signal is generated by a particular event
  2. Signal is delivered to a task/process
  3. Signal is handled
- Design options:
  - Deliver the signal to the thread to which the signal applies
  - Deliver the signal to every thread in the task
  - Deliver the signal to certain threads in the task
  - Assign a specific thread to receive all signals for the task

Thread Pools

- Create a number of “worker threads” in a pool where they are waiting for work
- You might need different pools of worker threads
- Advantages:
  - Usually slightly faster to service a request with an existing waiting thread instead of creating a new pop-up thread before starting the service
  - Allows the number of threads in the application(s) to be bound to the size of the pool
- Disadvantage:
  - Some of these worker threads might never be needed

Problems: Programming Threads



Conflicts between threads using a global variable, e.g. Unix's errno (contains error code of current system call)

Thread Control Block (TCB)

Thread Representation

Implementing thread control, we need a data structure representing a thread, i.e. something representing the existence of a thread including its

TID = thread identifier (see our passport)

Why and when do we really need a TID?

Hint: Compare a TCB with your passport

- Crossing borders
- Controlling/arresting suspicious people
- *Additional unique and **non forgeable** attributes?*

Thread Representation

TID all together with other useful information characterizing a thread is collected within the

thread control block or TCB

Definition:
A thread attribute describes or characterizes a thread

Example:
A thread intensively using I/O is called “I/O-bound”

Remark:

Different systems might have different attributes in their TCBs

TCBs can vary concerning size and/or internal structure

Minimal TCB

Thread Identifier (TID)
Instruction Pointer (IP)
Stack Pointer (SP)
Status Flags (SF)

Don’t say program counter!!!

<IP, SP, SF> = minimal context of a thread

Potential TCB Attributes

- Thread identifier TID
- Context related
  - User registers
  - Kernel registers
- Scheduling related
- Stack related
- Additional private “resources”
  - private global data

Thread Control Information

- User-Visible Registers
  - Stack-Related
  - General Purpose
  - Floating-Point
  - Index

- Control and Status Registers

Stacks are used to support procedure and system calls (establishing local variables, transfer of parameters etc.)

A stack pointer points to the top of the stack.

Thread Control Information

- User-Visible Registers
  - Stack-Related
  - General Purpose
  - Floating-Point
  - Index
- Control and Status Registers

Instruction Pointer (address of next instruction)

Condition Codes (results of previous instruction, e.g. equal bit, overflow bit)

Status Information (execution mode etc.)

Thread Control Information

- Events related to a thread's execution, e.g. waiting for a specific I/O result ($\Rightarrow$ scheduling)
- Priorities
- Inter-Process Communication (IPC)
- Mapping Information (task-specific)
- Current resource holder (e.g. lock holder)
- Resource ownership and utilization (task-specific)

Implementing Sets of TCB's

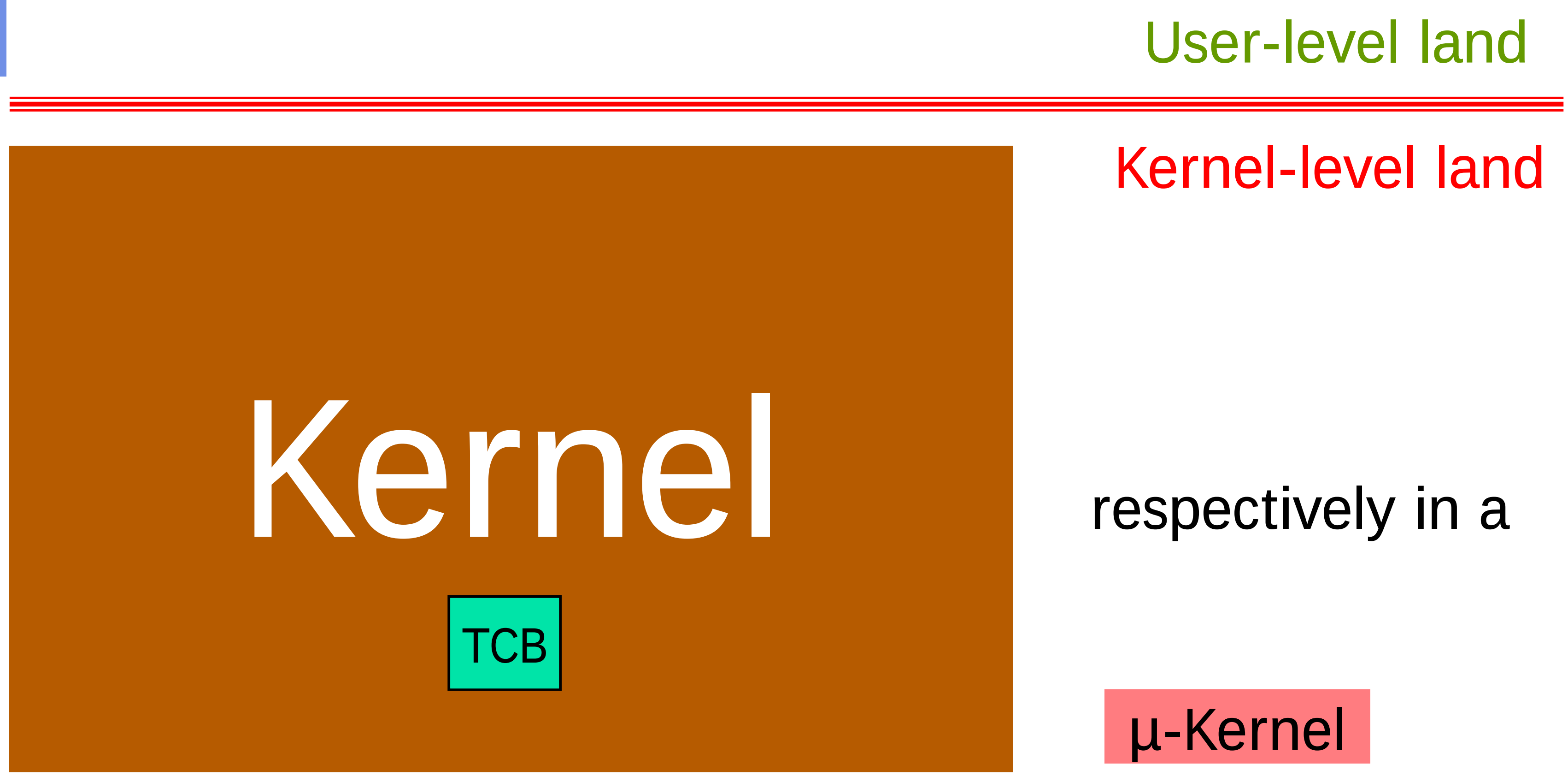
Implementation techniques

- Contiguous table of TCB's (thread table)
  - Real array
  - Virtual array
- Structured list of TCB's

<u>Hint:</u>

Considering different system constraints, discuss appropriate data structures for implementing a structured list of TCBs

Traditional Location of KLT TCBs



Literature

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