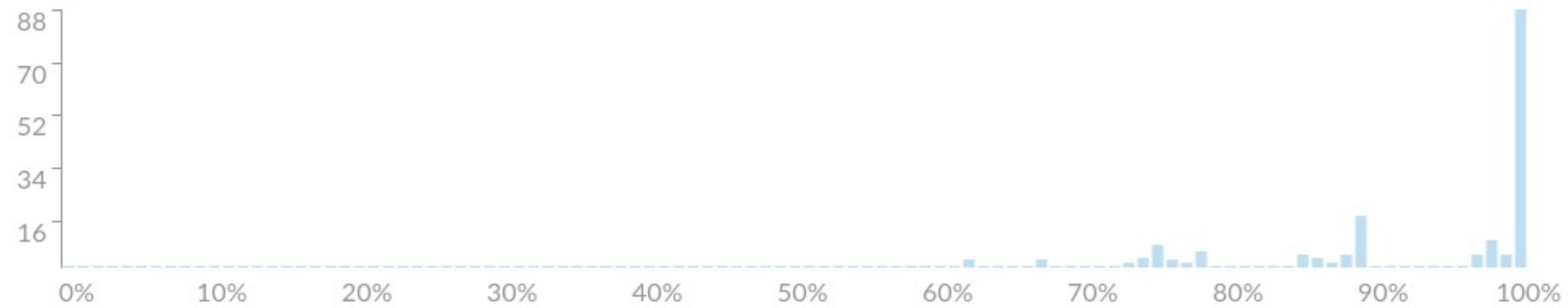
Prof. Sibin Mohan

Spring 2022 | Lec. 11: Multithreading and Synchronization

Adapted from content originally created by: Prof. Yeongjin Jang

Quiz 2

Average Score	High Score	Low Score	Standard Deviation	Average Time
94%	100%	62%	0.87	45:25



Administrivia

- Lab 3 due date extended: **May 20, 2022** [**Friday**] at **11:59 PM**!
  - Lots of office hours/lab sessions this week and next

- Watch all **Tutorials** and go through the slides/textbook

Virtualization → Concurrency

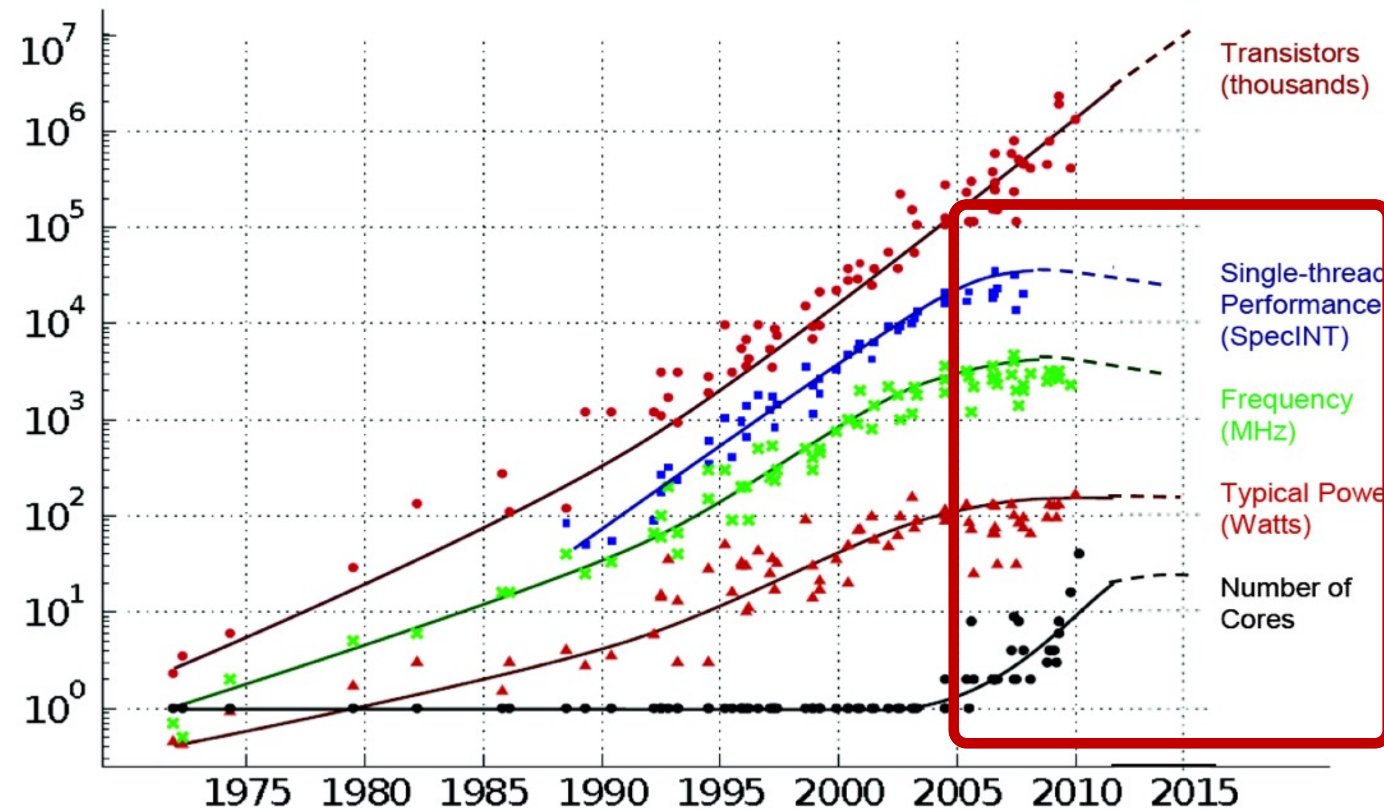
Topics discussed today

- Process / Thread
- Synchronization via Mutex
- Concurrency bugs / Deadlock

- Why is concurrency useful?
- Difference between Process/Thread
- Data racing issues
- Synchronization (Mutual Exclusion)

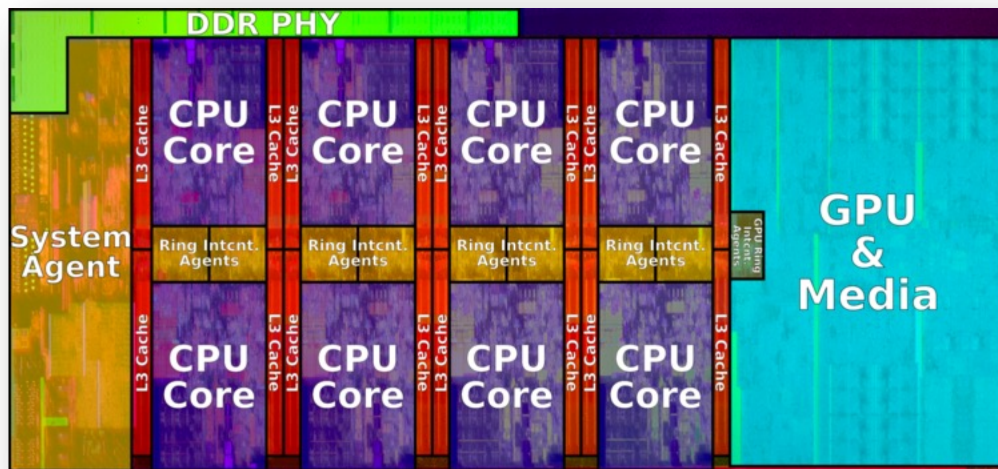
Single-threaded CPU Performance

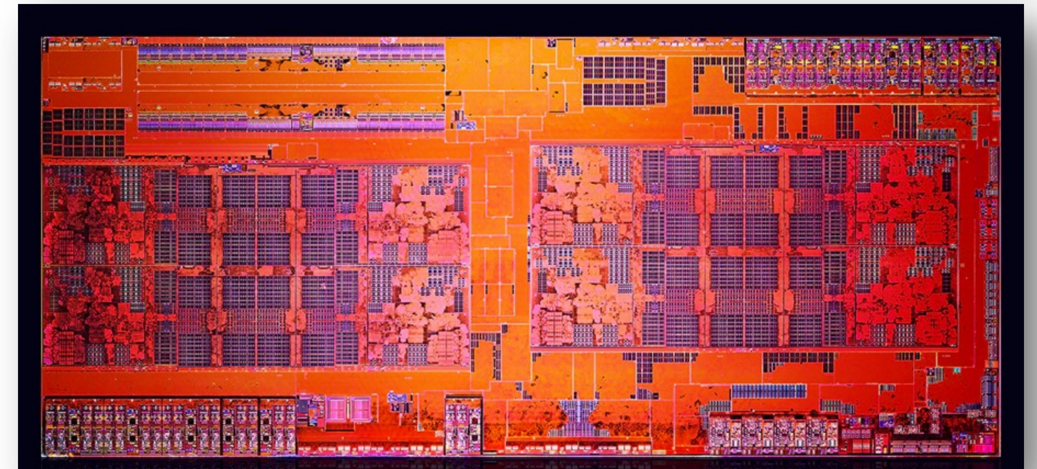
- # of transistors
  - Increases linearly
- Performance
  - **No longer increasing linearly**



CPU Speed Capped by Frequency/Power

- How to get a better performance?



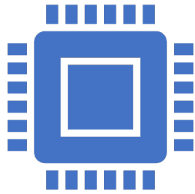


CPU Speed Capped by Frequency/Power

- How to get a better performance?

Motivation for Concurrency

vs



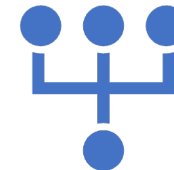
Trend in CPU

Same clock speed (3~5Ghz), **more CPU cores**

Increase System Performance

Run **many jobs at the same** time

fully utilize multiple cores

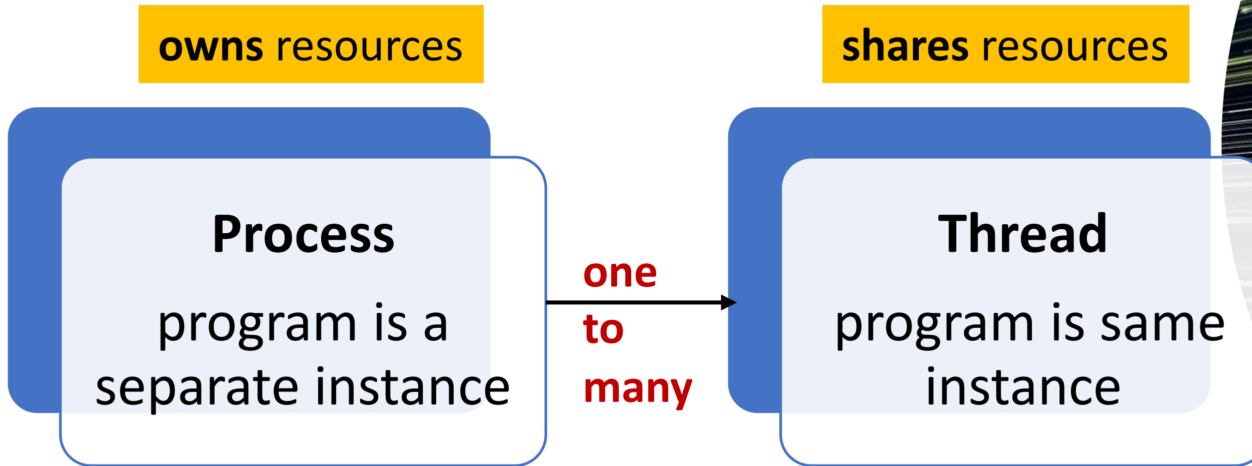


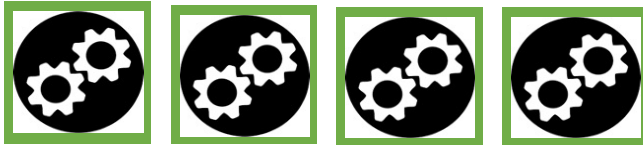
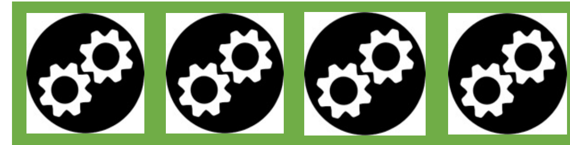
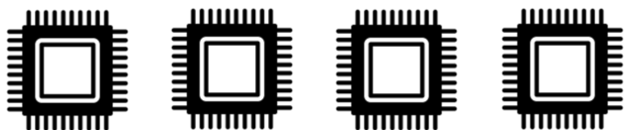
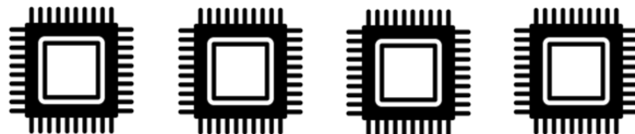
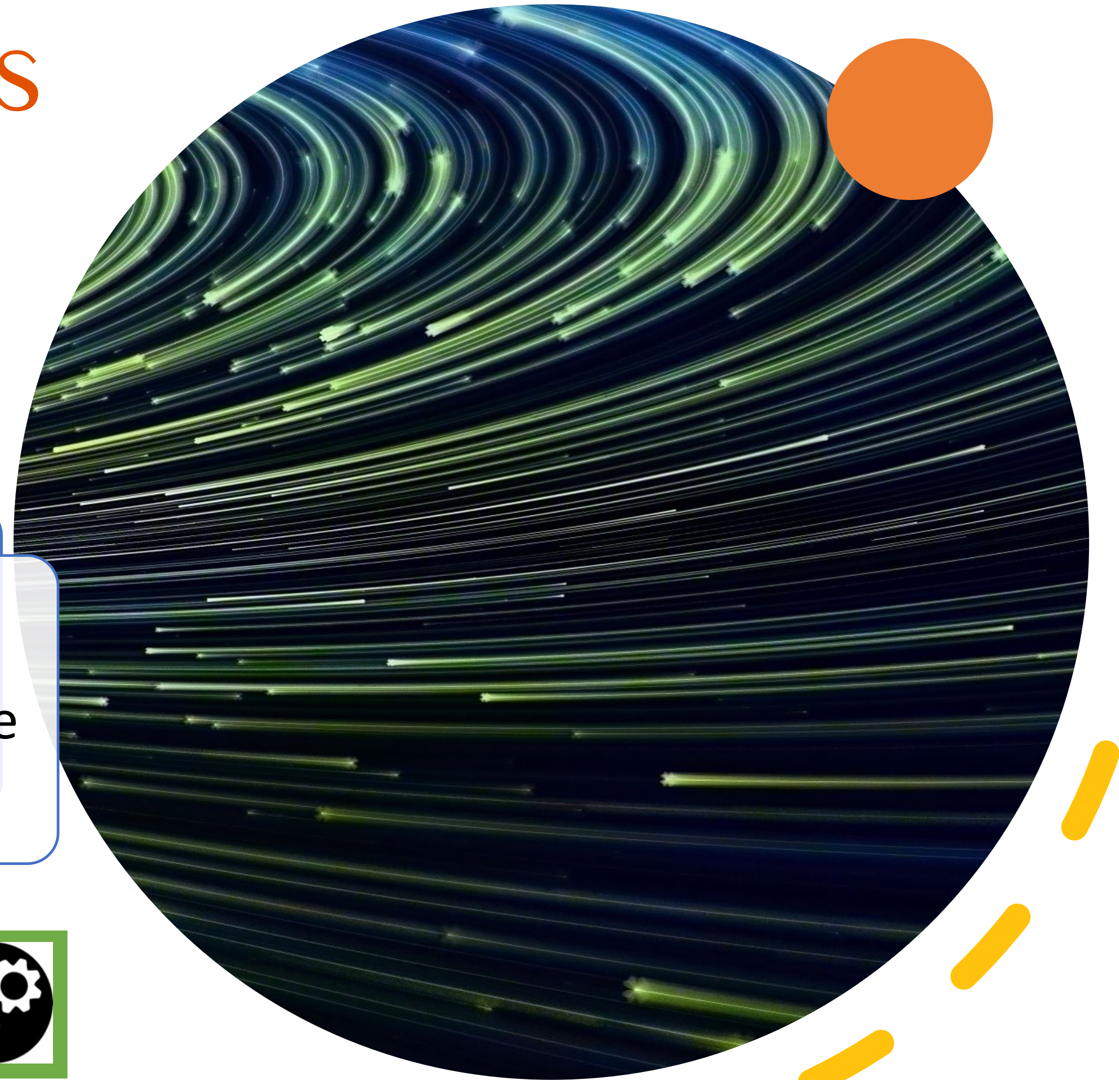
How to increase application performance?

Run **multiple functions as separate jobs** at the same time!

Processes, Threads

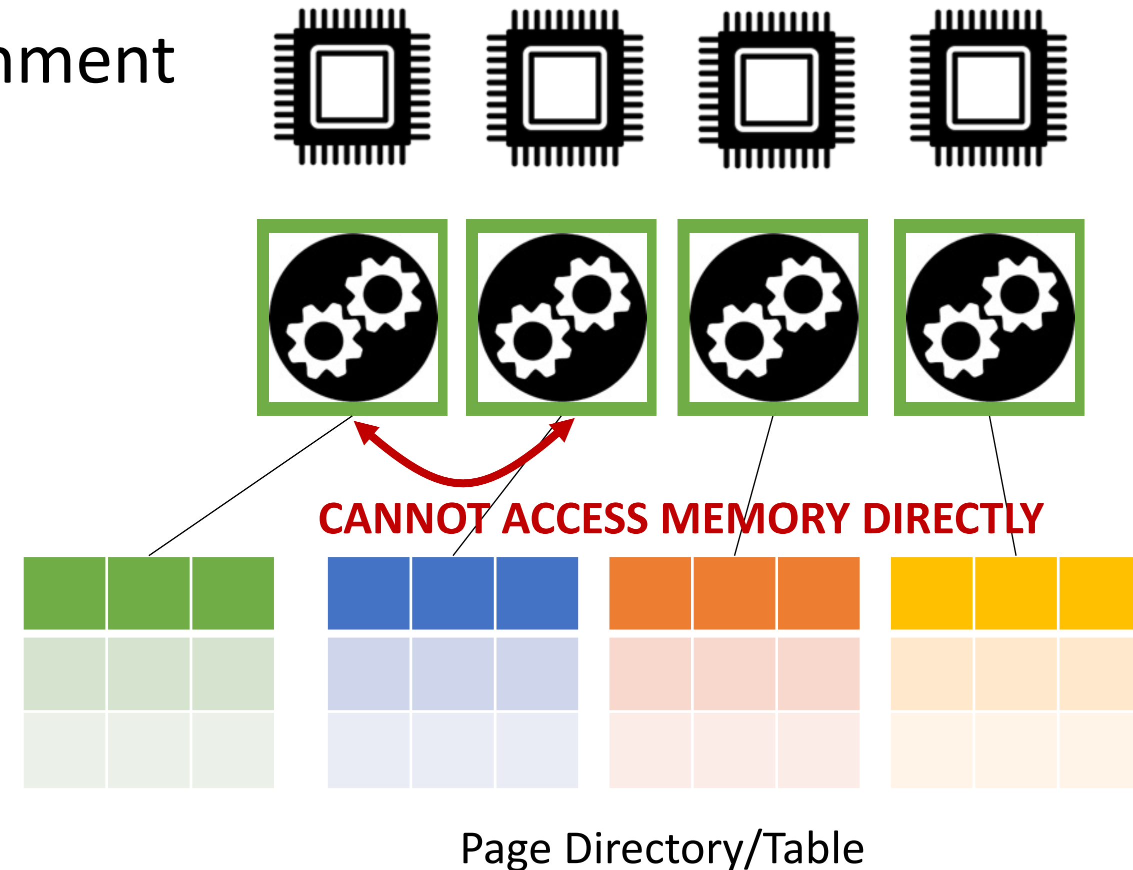
Concurrency Options



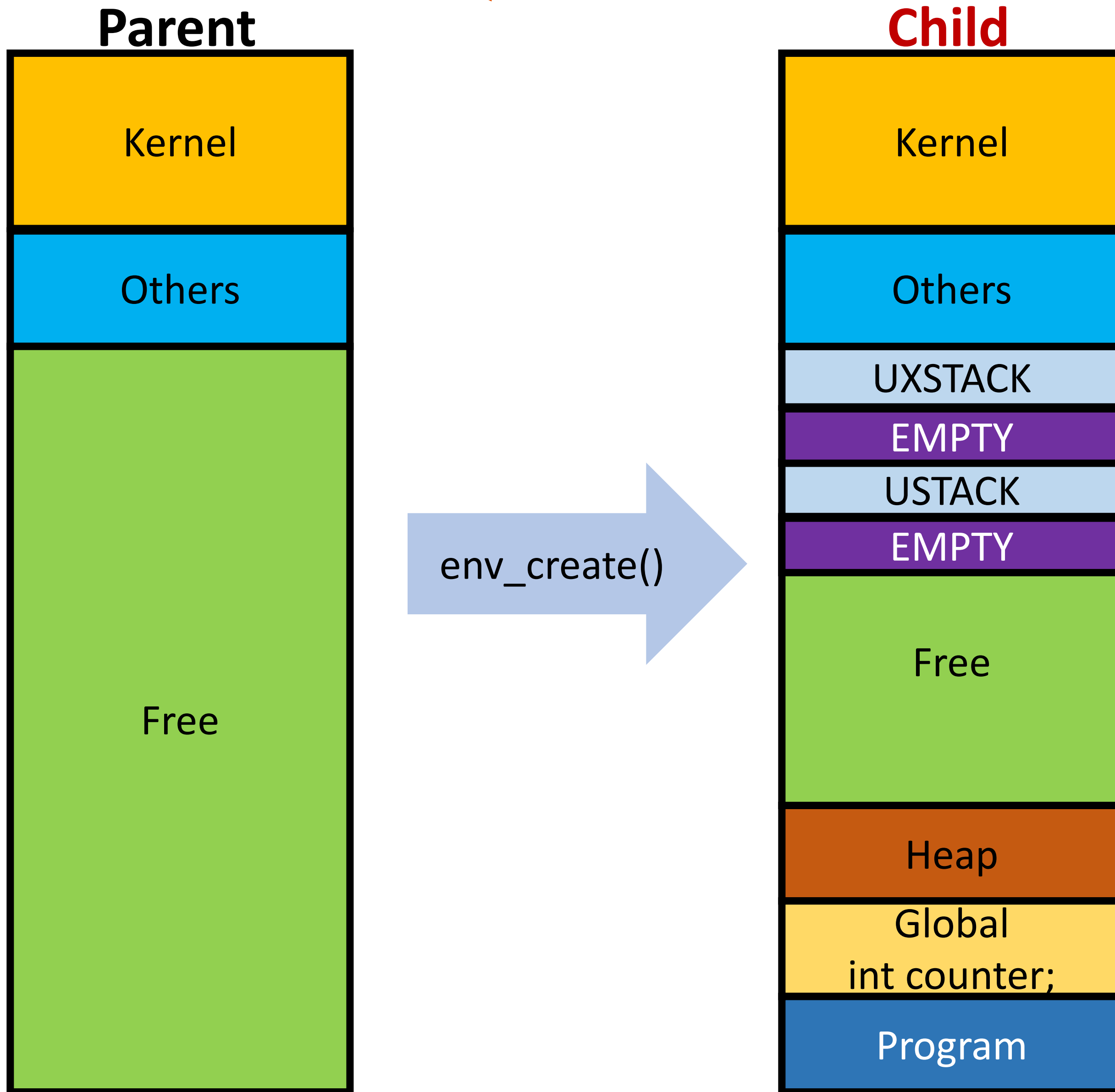






Process

- Each execution runs in isolated environment
- Does not share memory space
  - Each process its has own page table
- Inter-Process Communication
  - for data sharing
  - file, pipe, socket(), shared memory, etc.

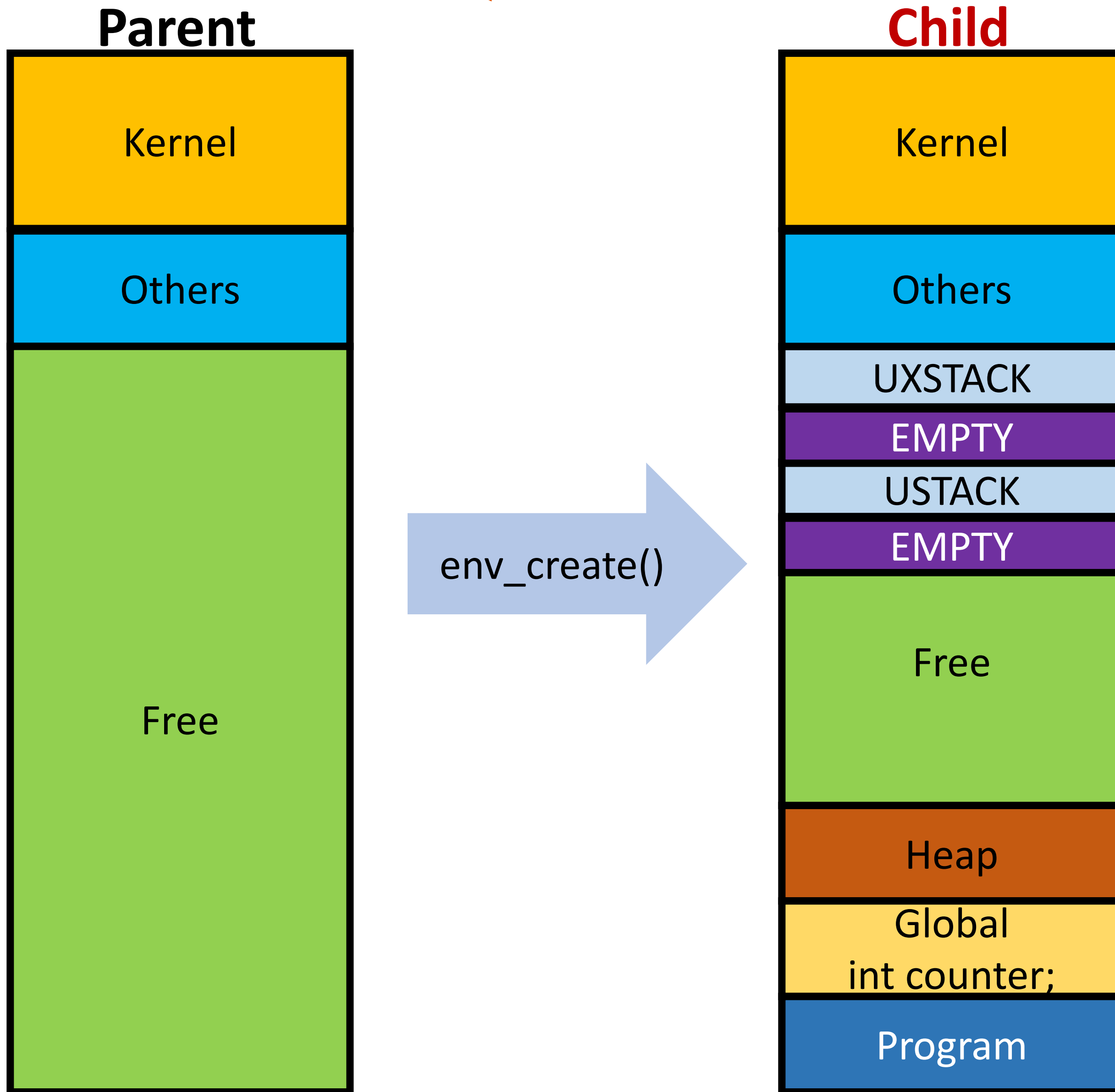


Process (Environment in JOS)



Process creates a **new private** memory space

Process (Environment in JOS)

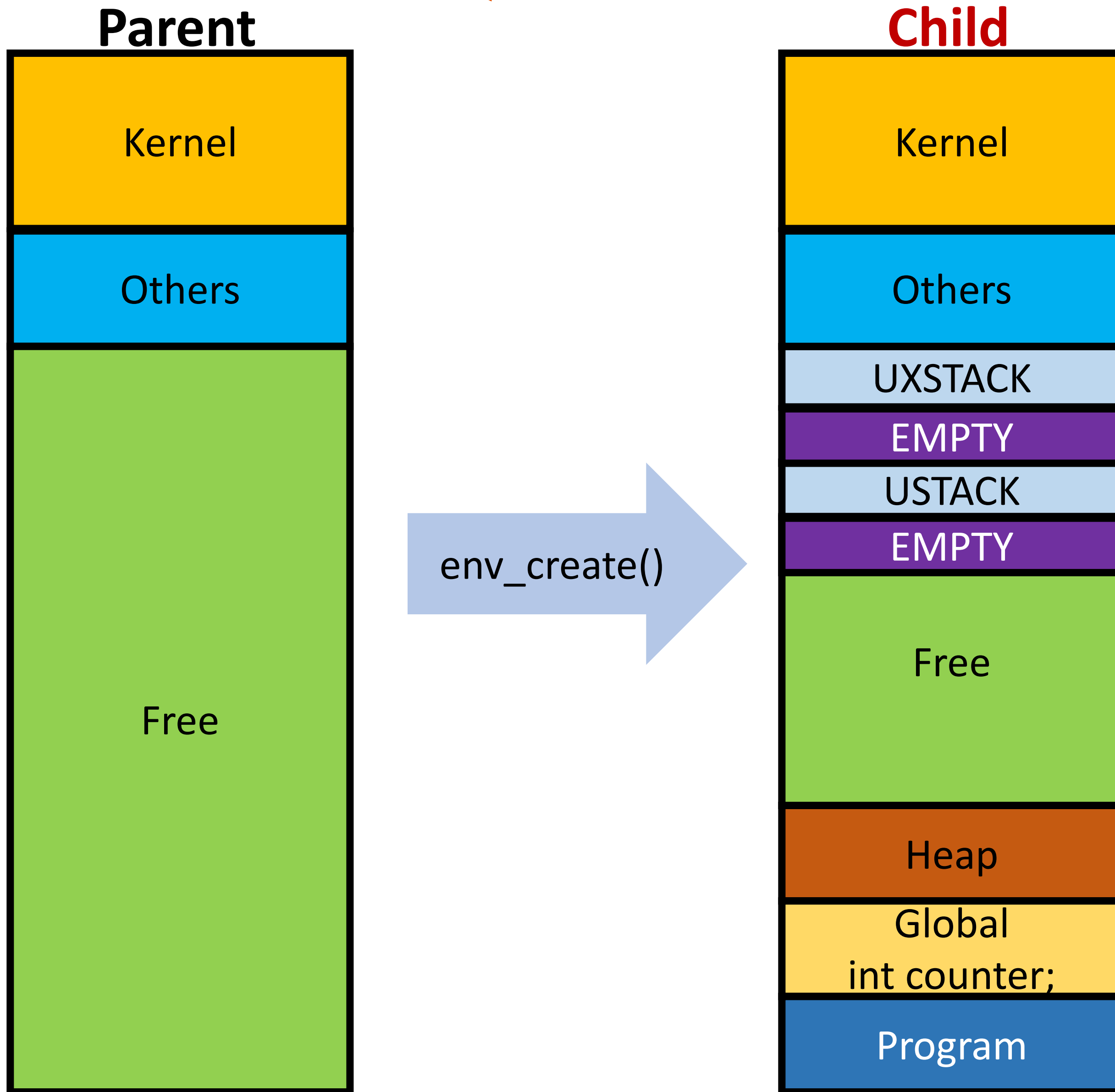


Process creates a **new private** memory space

```
int foo(arguments)
{
      some code ;

      some other code ;
}
```

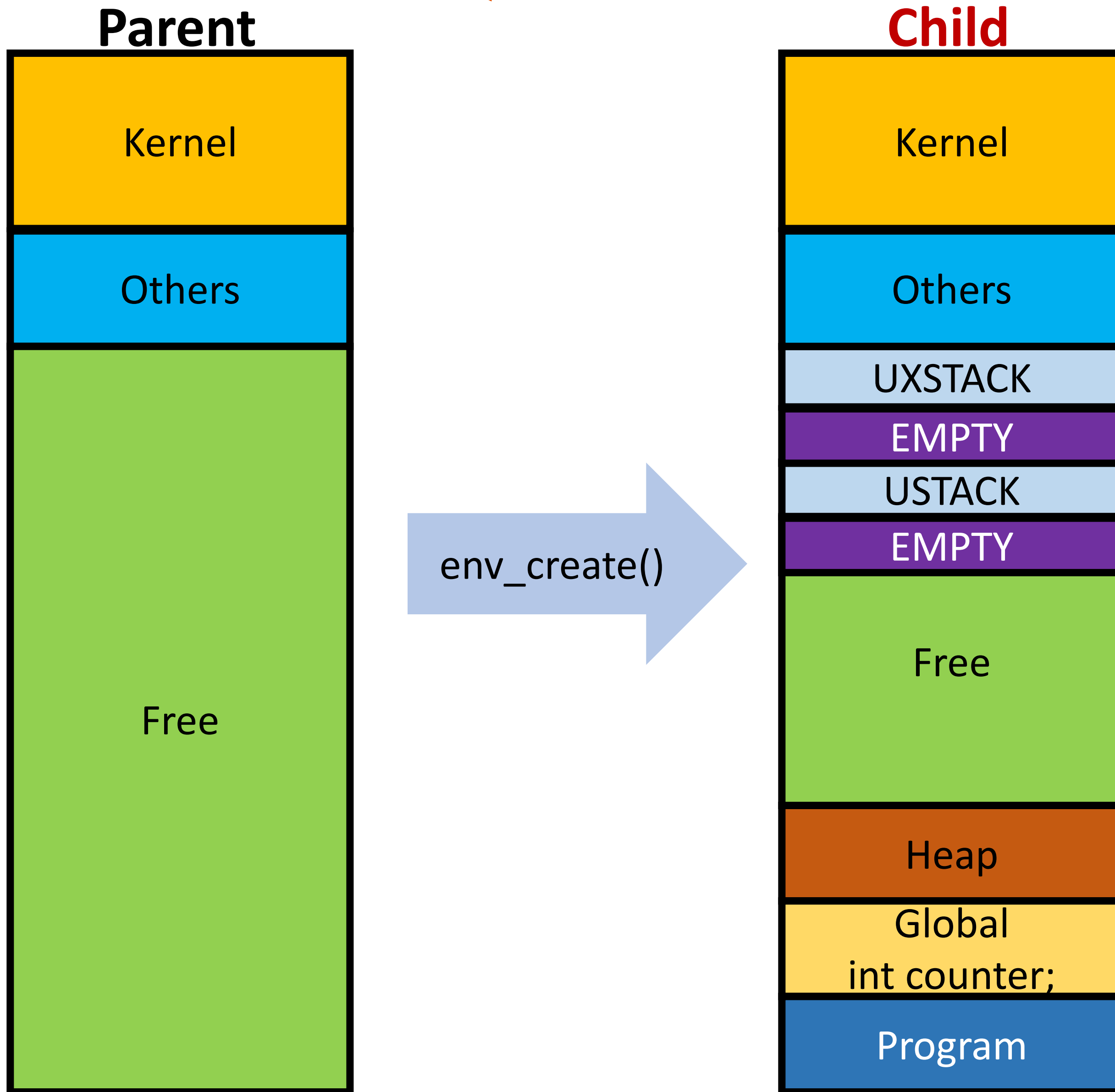
Process (Environment in JOS)



Process creates a **new private** memory space

```
int foo(arguments)
{
    some code ;
    fork() ;
    some other code ;
}
```

Process (Environment in JOS)



Process creates a **new private** memory space

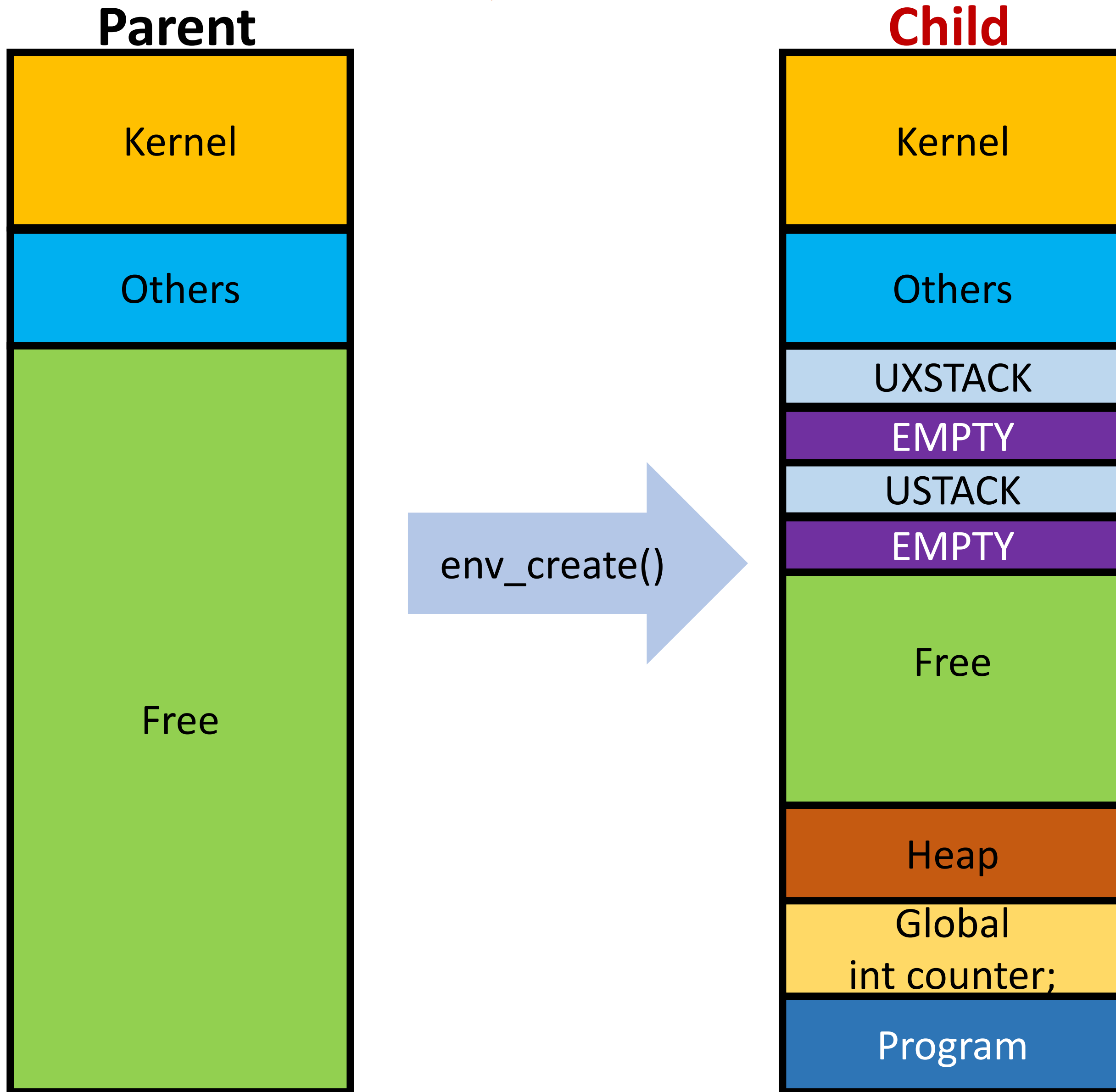
Parent

```
int foo(arguments)
{
    some code ;
    fork() ;
    some other code ;
}
```

Child

```
int foo(arguments)
{
    some code ;
    fork() ;
    some other code ;
}
```

Process (Environment in JOS)



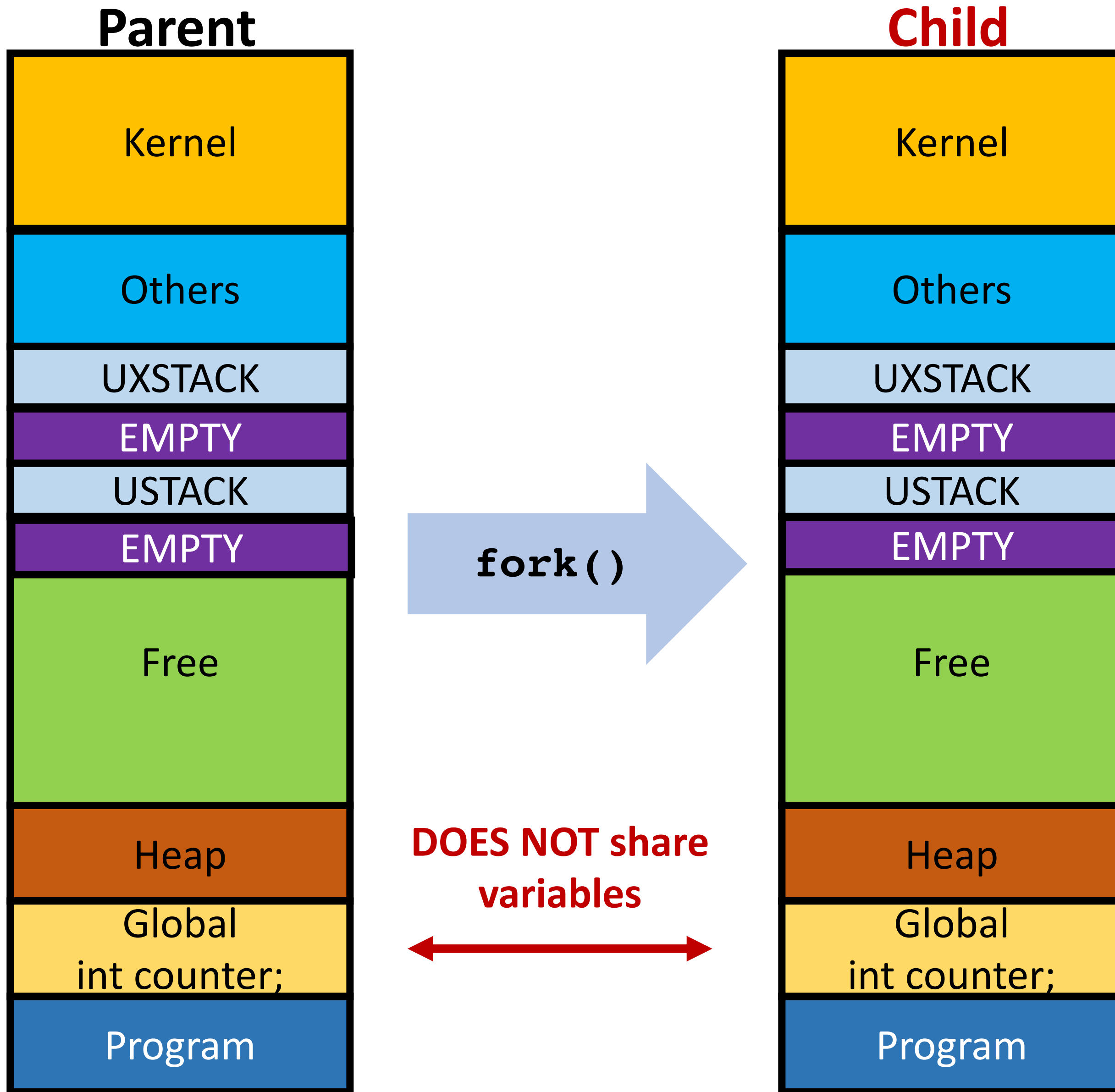
Process creates a **new private** memory space

```
int foo(arguments)
{
     some code ;
     pid_t pid = fork() ;
     if (pid == parent)
        parent_function(arguments);
     else
        child_function(arguments);
}

int parent_function(arguments)
{...}

int child_function(arguments)
{...}
```

Process (Environment in JOS)



Fork() creates new process by copying memory space
Process creates a new PRIVATE memory space

```c
#include <stdio.h>
#include <unistd.h>

int counter;
volatile int value = 1;

void countup() {
    for(int i=0; i<1000000; ++i) {
        counter += value;
    }
}

int main() {
    pid_t pid = fork();
    countup();
    printf("%s: %d\n", pid ? "Parent" : " Child", counter);
}
```

```
Parent: 1000000
 Child: 1000000
```

Process | Pros vs Cons

Pros	Cons
Parallelism without program modifications	More memory requirements → one per process

Process | Pros vs Cons

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Parallelism without program modifications	More memory requirements → one per process
Separation of memory spaces [**isolation**]	Separation of memory spaces [**no data sharing**]

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Easy to start → fork()	Each process needs to be ended separately

Process | Pros vs Cons

Pros	Cons
Parallelism without program modifications	More memory requirements → one per process
Separation of memory spaces [**isolation**]	Separation of memory spaces [**no data sharing**]
Easy to start → fork()	Each process needs to be ended separately

- Any write will incur memory duplication even in CoW fork()
- Inter-process Communication (IPC) is available, but slow
- Suitable for **parallel 'isolated'** execution
- Not suitable for parallel execution on **shared data**

Two Issues

Parallelism

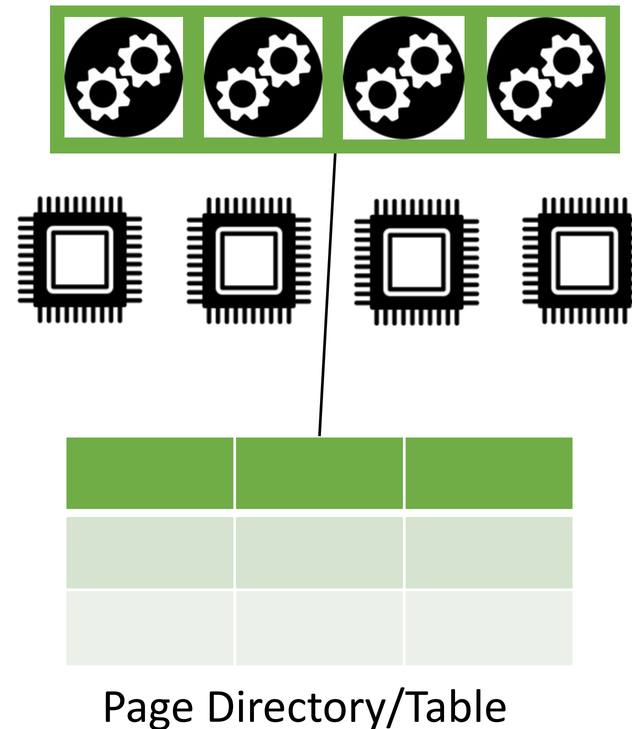
Share a memory space

Threads!

Threads

Process
- creates a new **private** memory space
- runs concurrently

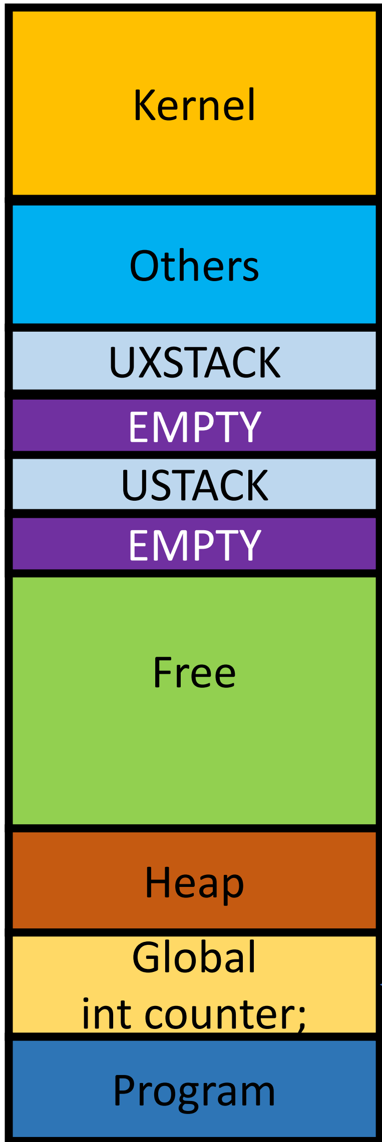
- What is a thread?
  - creates a **shared** memory space
  - runs **concurrently**
- **Sharing**
  - **access the same memory space**
  - e.g., global variables, etc.
- A process contains 1 or more threads

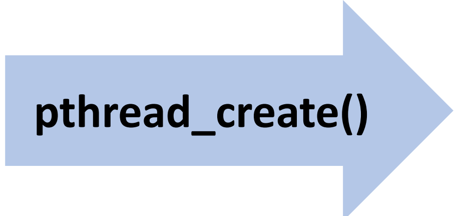


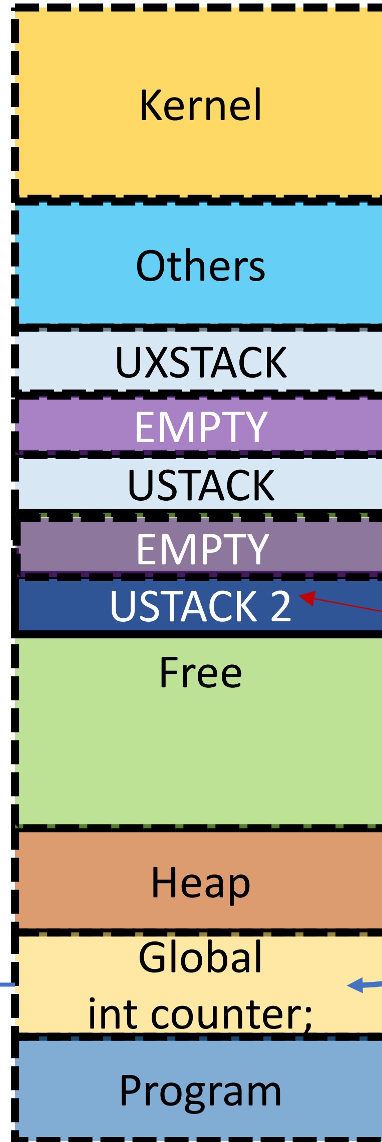
Thread | Sharing Memory

- **Process** Creation via `fork()`
  - Naïve design
    - copy all physical pages
    - create **a new page directory/table**
    - has same virtual mapping (to new, corresponding physical pages)
  - Copy-on-write
    - do not copy all physical pages but keep the same mappings
    - provide a private copy when write on COW page occurs
- **Thread Creation**
  - Get **a new execution environment**
  - Assign **the same page directory/table** (e.g., assign the **same CR3**)
  - Create **a new stack / storage for register context** to store execution context separately
  - Use **less memory** than fork()

Thread







The same variable

Add a new stack!

Adding value

```
#include <stdio.h>
#include <unistd.h>
#include <pthread.h>

int counter;
volatile int value = 1;

void * countup(void *arg) {
    for(int i=0; i<1000000; ++i) {
        counter += value;
    }
    printf("%s: %d\n", arg ? "Parent" : " Child", counter);
}

int main() {
    pthread_t thread;
    pthread_create(&thread, NULL, countup, NULL);
    countup((void*) 1);
    pthread_join(thread, NULL);
}
```

Thread | Pros vs Cons

Pros	Cons
Easier to share memory across threads	No isolation! Programmers must be careful

Thread | Pros vs Cons

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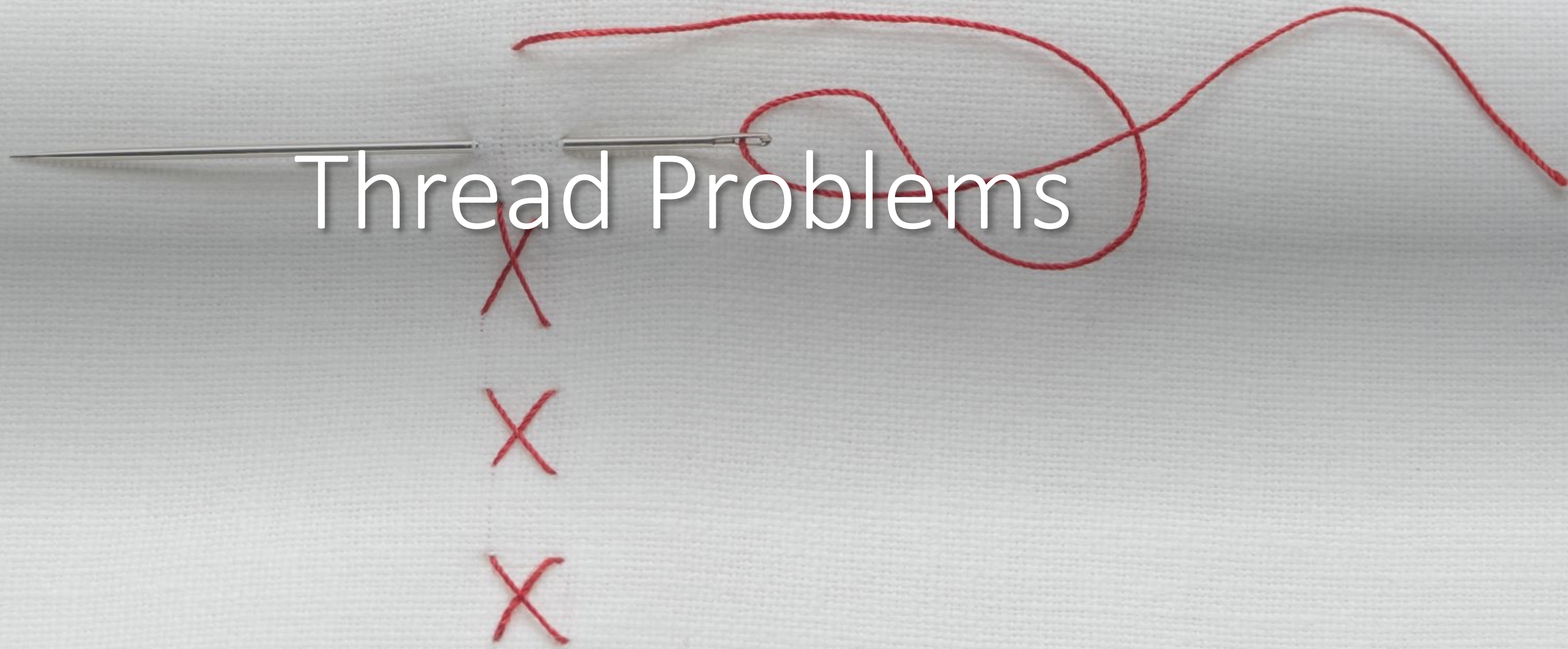
Less memory, compared to fork [only new stack, registers]	All threads share same address space

Thread | Pros vs Cons

Pros	Cons
Easier to share memory across threads	No isolation! Programmers must be careful
Less memory, compared to fork [only new stack, registers]	All threads share same address space

- Suitable for parallel execution on shared data
- Not suitable for having a private execution

Thread Problems



Thread

Process (before)	Process (after pthread_create())
Kernel	Kernel
Others	Others
UXSTACK	UXSTACK
EMPTY	EMPTY
USTACK	USTACK
EMPTY	EMPTY
	USTACK 2
Free	Free
Heap	Heap
Global int counter;	Global int counter;
Program	Program

pthread_create()

The same variable

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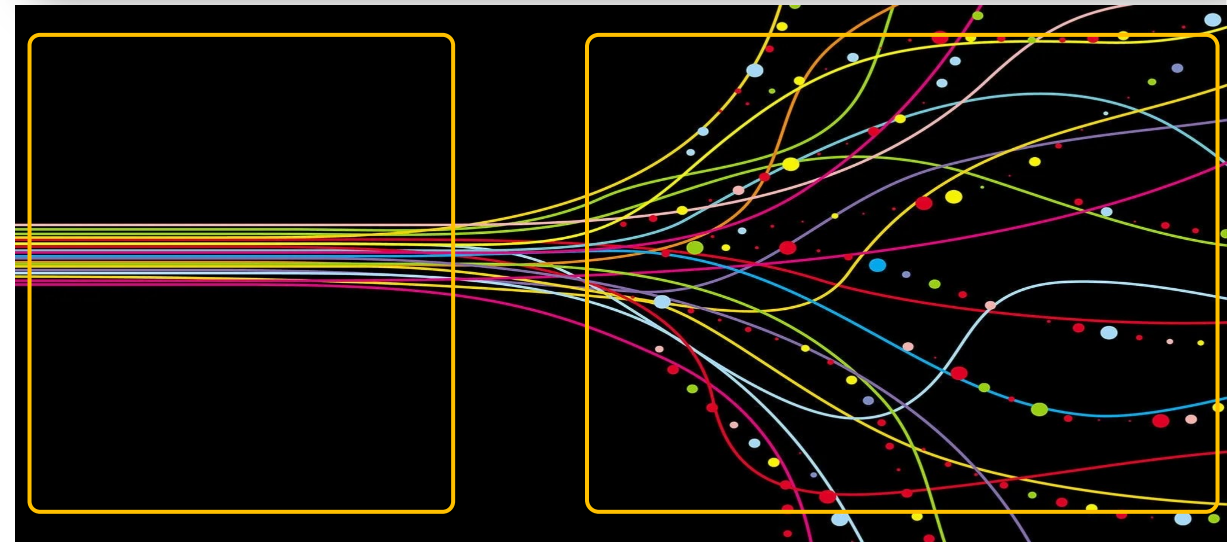
    countup((void*) 1);
    pthread_join(thread, NULL);
}
```

```
 Child: 1092487
Parent: 1221966
```

```
 Child: 975822
Parent: 1081479
```

Why not 2000000?



Data Race

- A thread’s execution result could be **inconsistent**
- **other threads intervene its execution!**

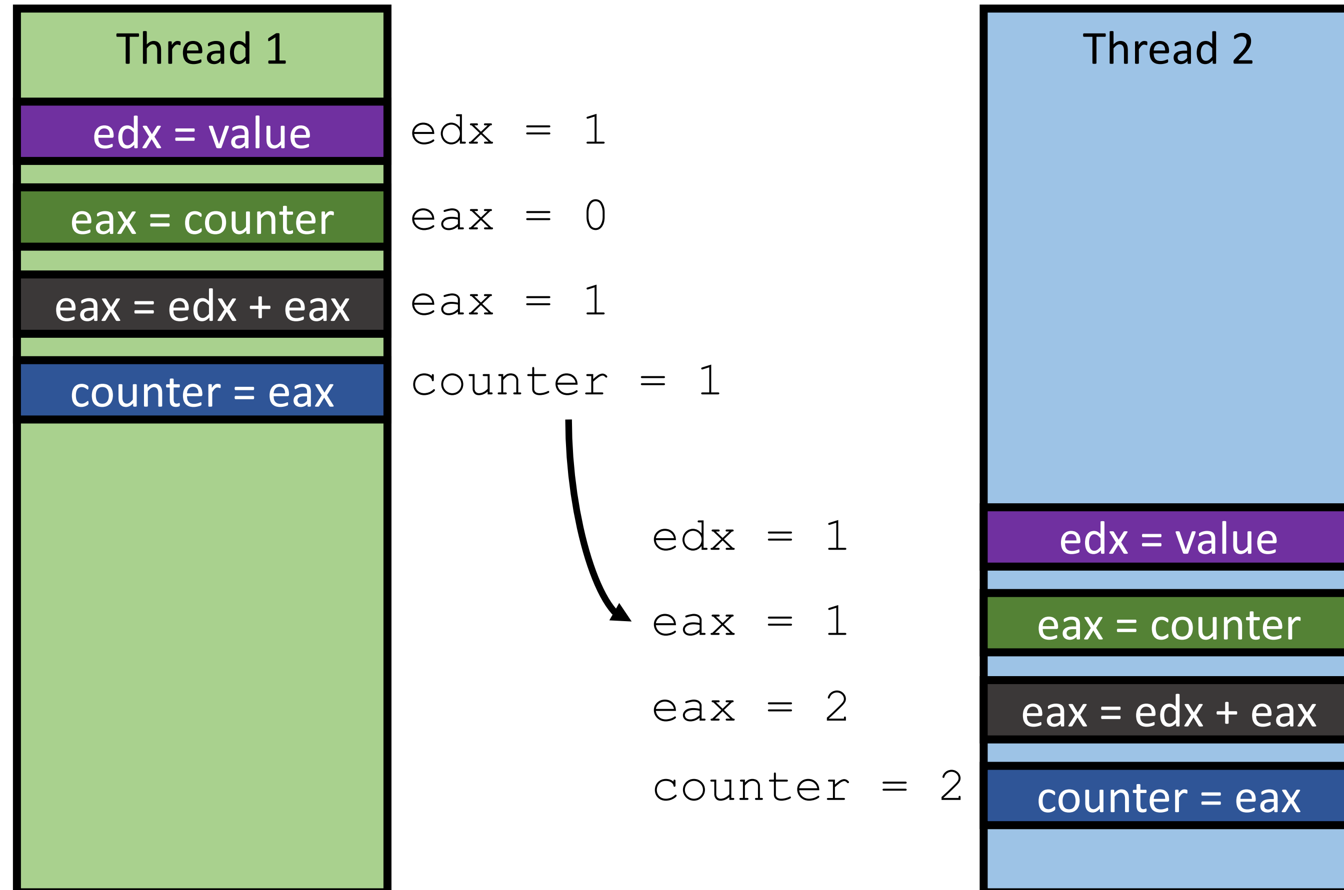
- counter += value
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`

```
mov     0x20087b(%rip),%edx        # 0x201010 <value>
mov     0x20087d(%rip),%eax        # 0x201018 <counter>
add     %edx,%eax
mov     %eax,0x200875(%rip)        # 0x201018 <counter>
```

Data Race Example (No race)

- counter += value
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`

- Assume at start,
  - counter = 0
  - value = 1



OK, consistent!

Data Race Example (Race cond.)

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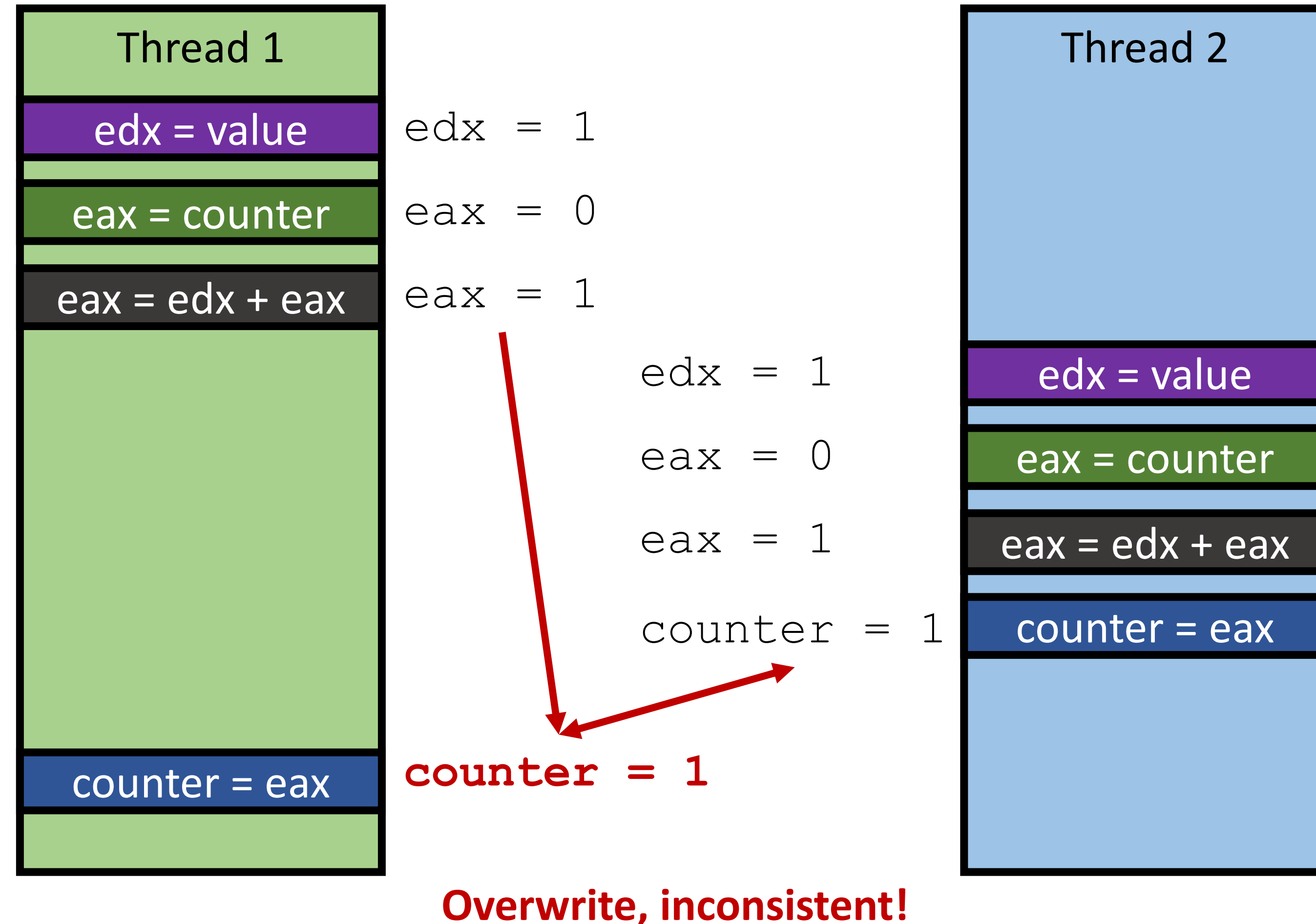

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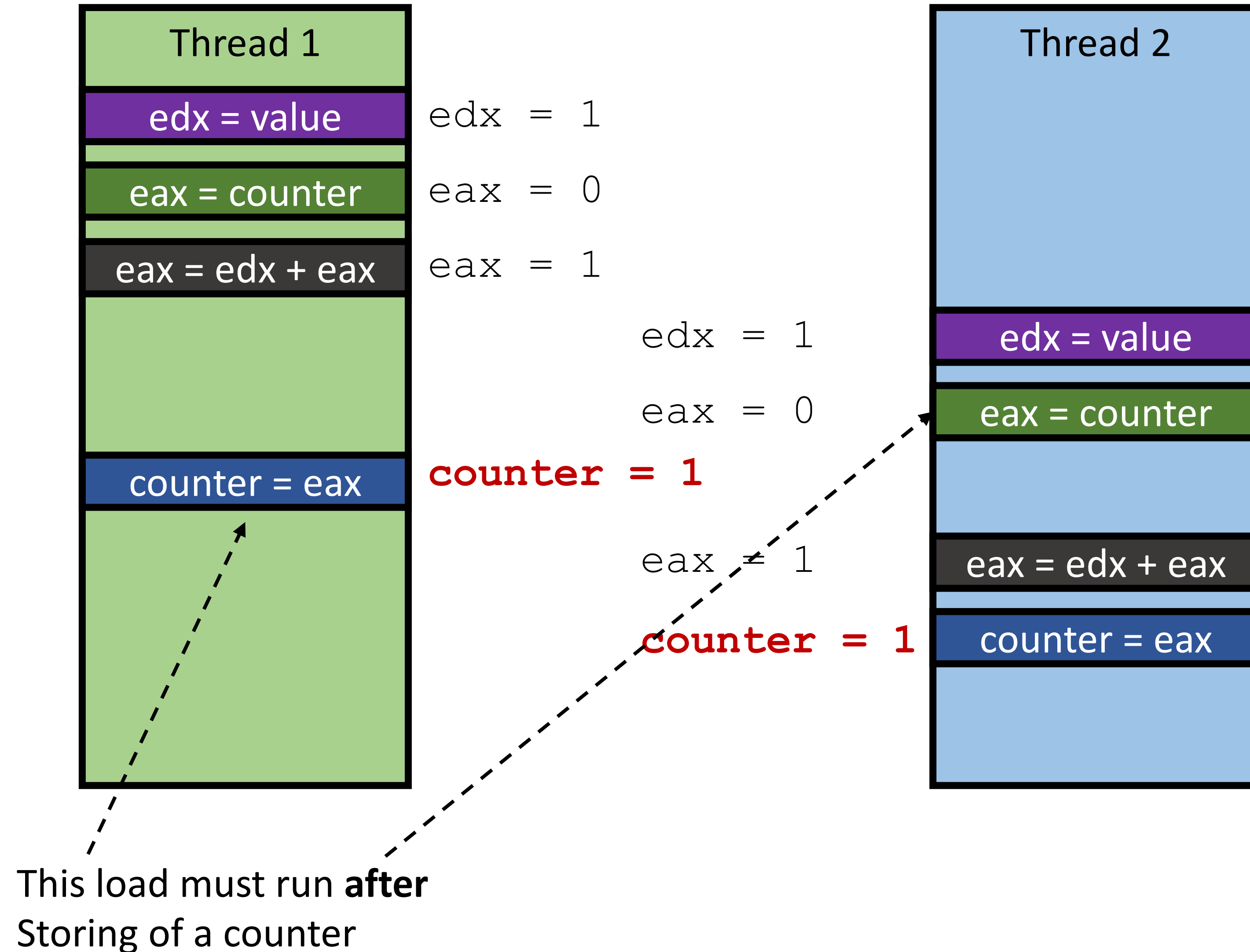

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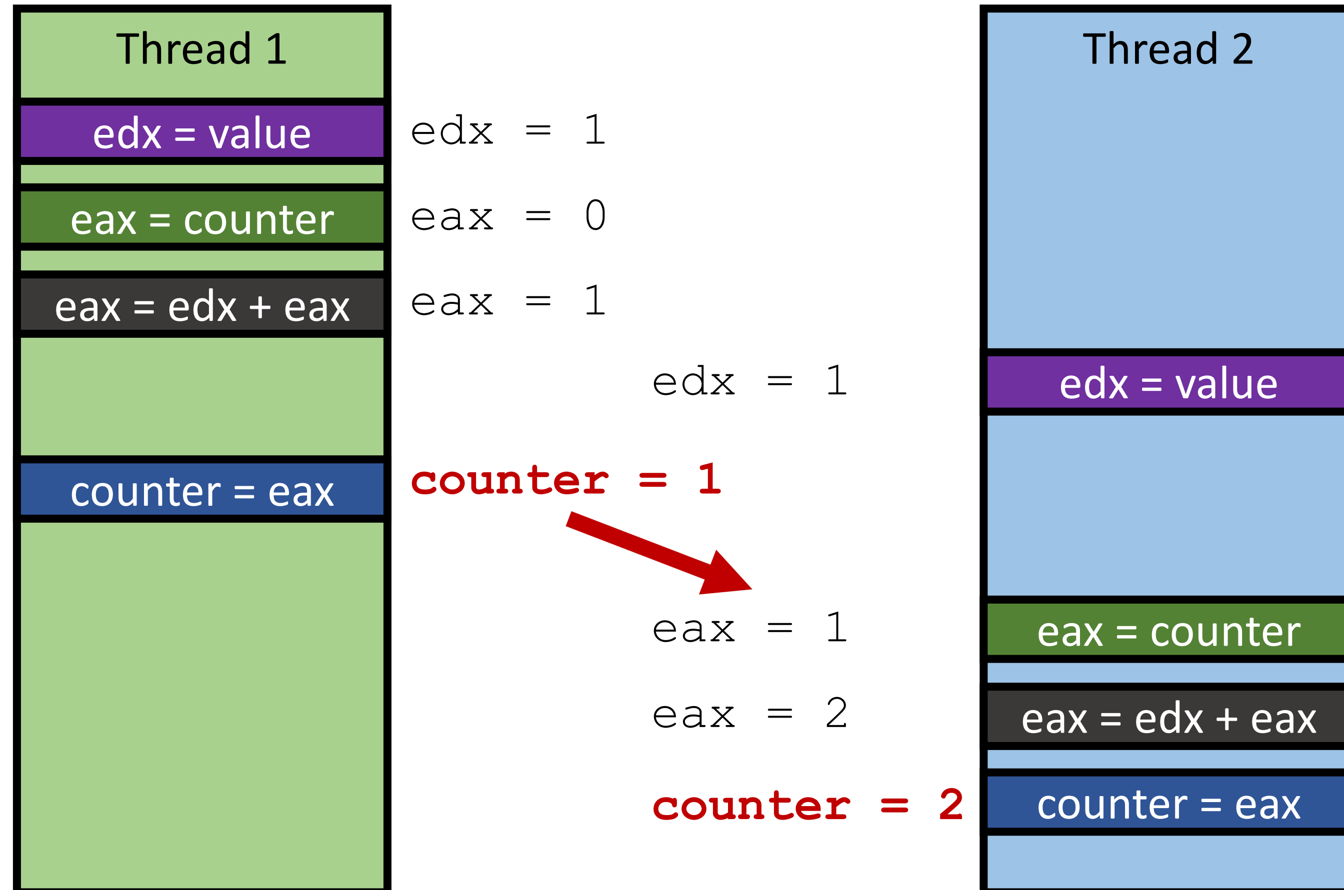
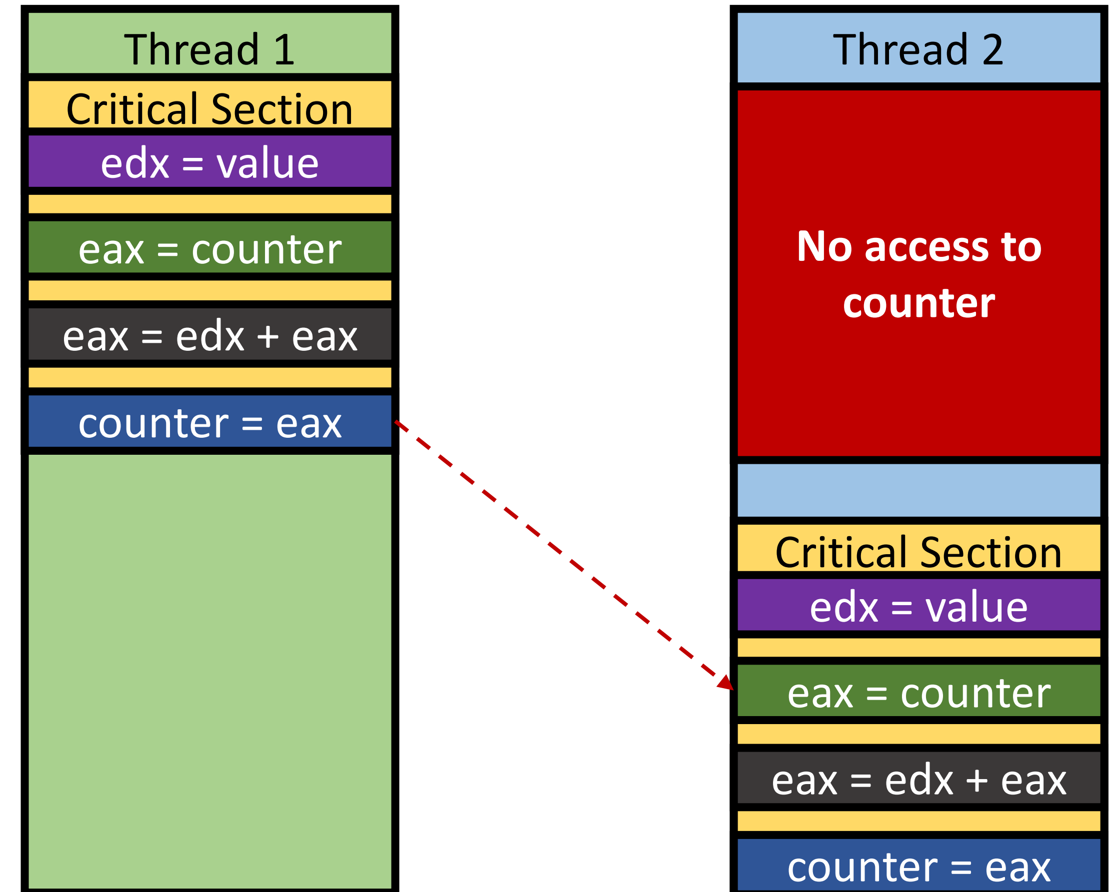


How to Prevent Data Races?

- Root-cause
  - A thread may load the '**previous version**' of shared data (counter = 0)
  - Before the previously running thread properly stores it (counter += 1)
- Store instruction of the previous **thread must finish**
  - before the load instruction of the next thread
- Solution
  - **Make all loads on shared variable wait until previous load-store finishes**
  - **Mutual exclusion**

How to Prevent Data Racing?

- **Mutual Exclusion / Critical Section**
  - Combine multiple instructions as a **chunk**
  - Let only one chunk execution run
  - Block other executions
  - Next execution
    - only after finishing all previous critical sections
- `pthread_mutex()` does this for you
  - learn how we can implement locks soon



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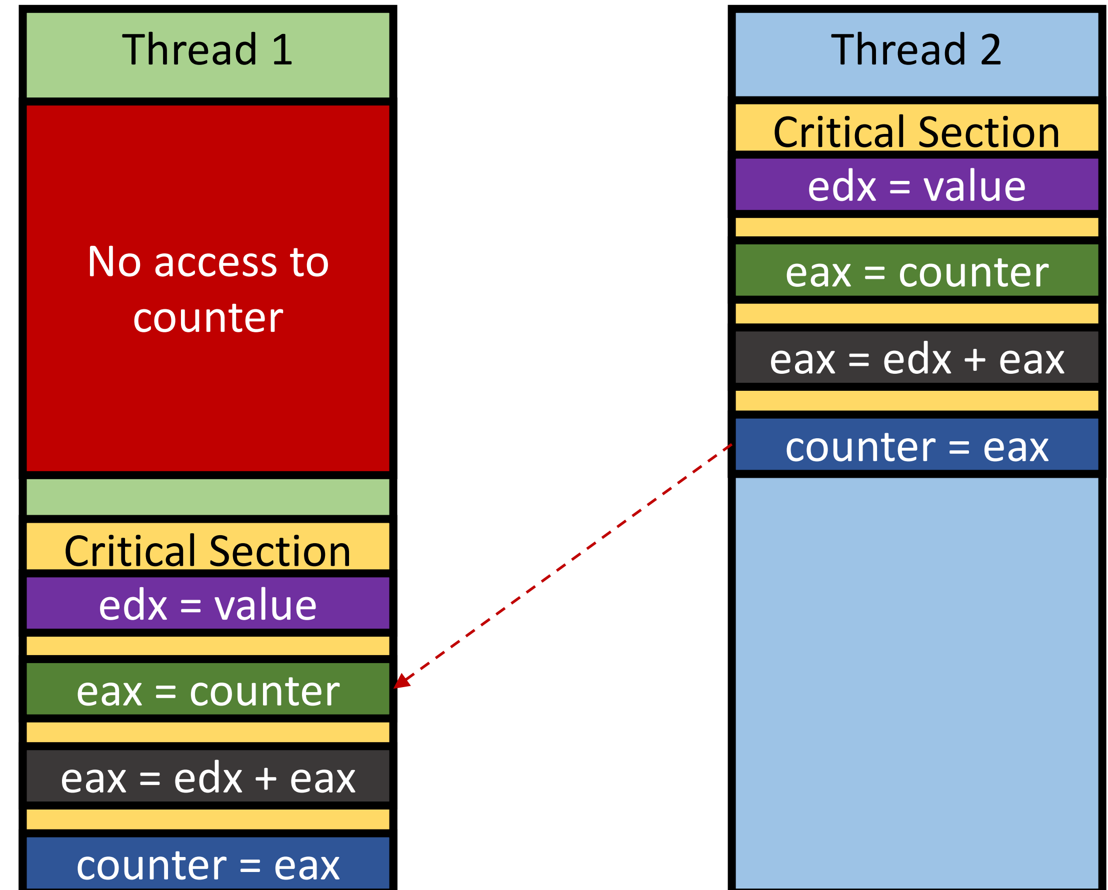
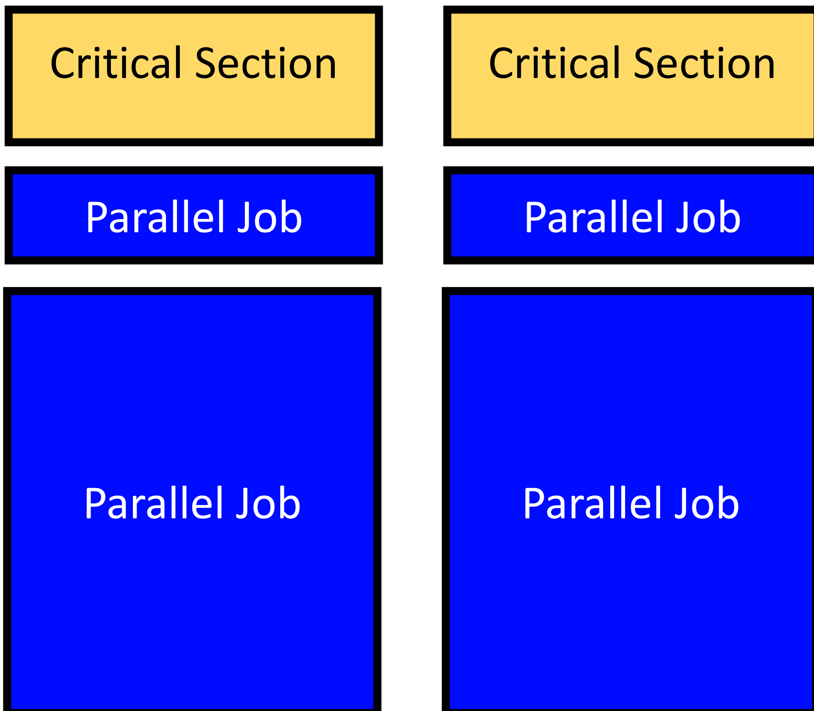


Would Mutex Render Threading Useless?

Thread 1
Critical Section
Critical Section
Critical Section
Critical Section
Critical Section

Thread 1	Thread 2
Critical Section	Exclusion
Exclusion	Critical Section
Critical Section	Exclusion
Critical Section	Exclusion
Exclusion	Critical Section

Use Critical Section **Only If Required**



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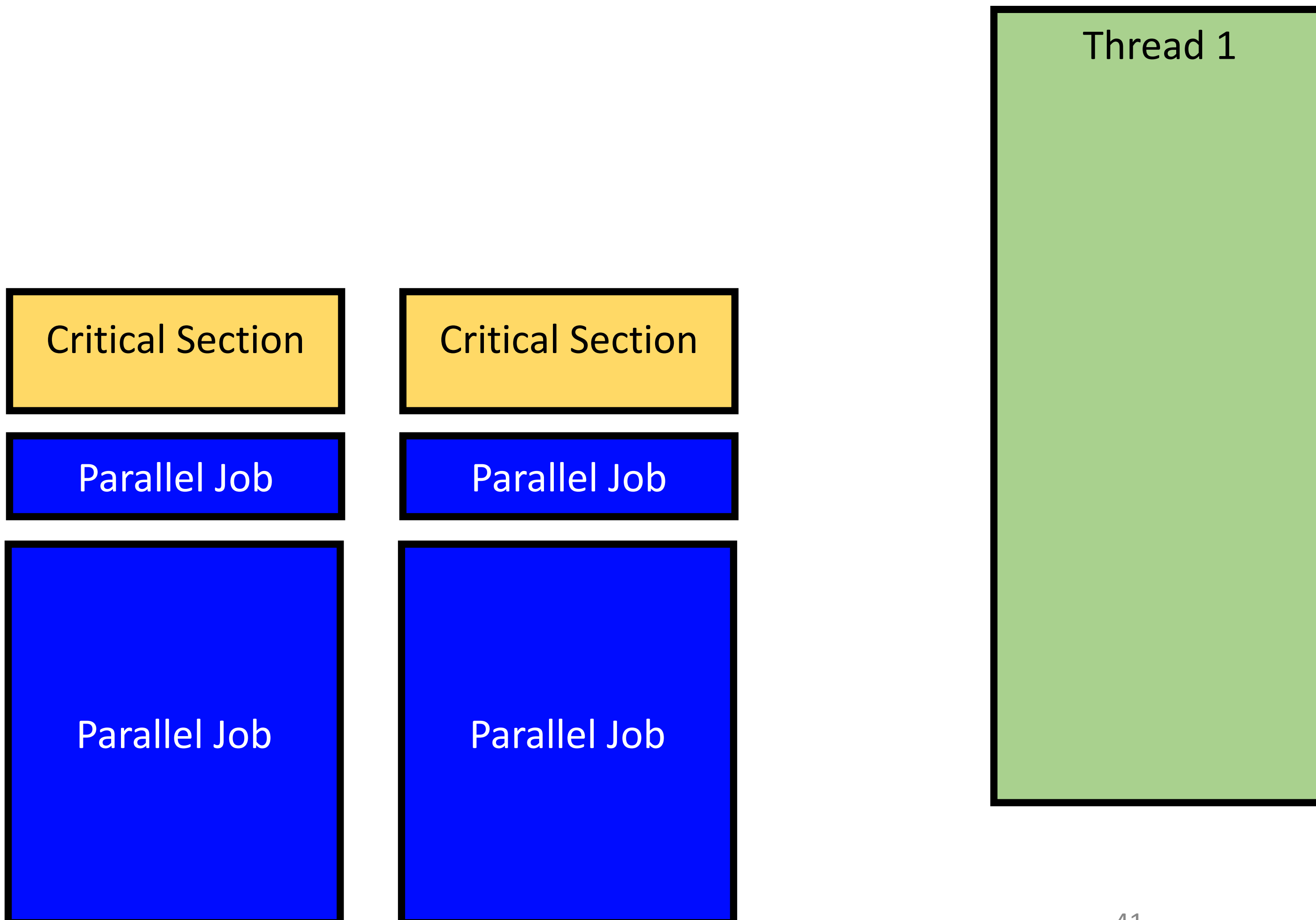

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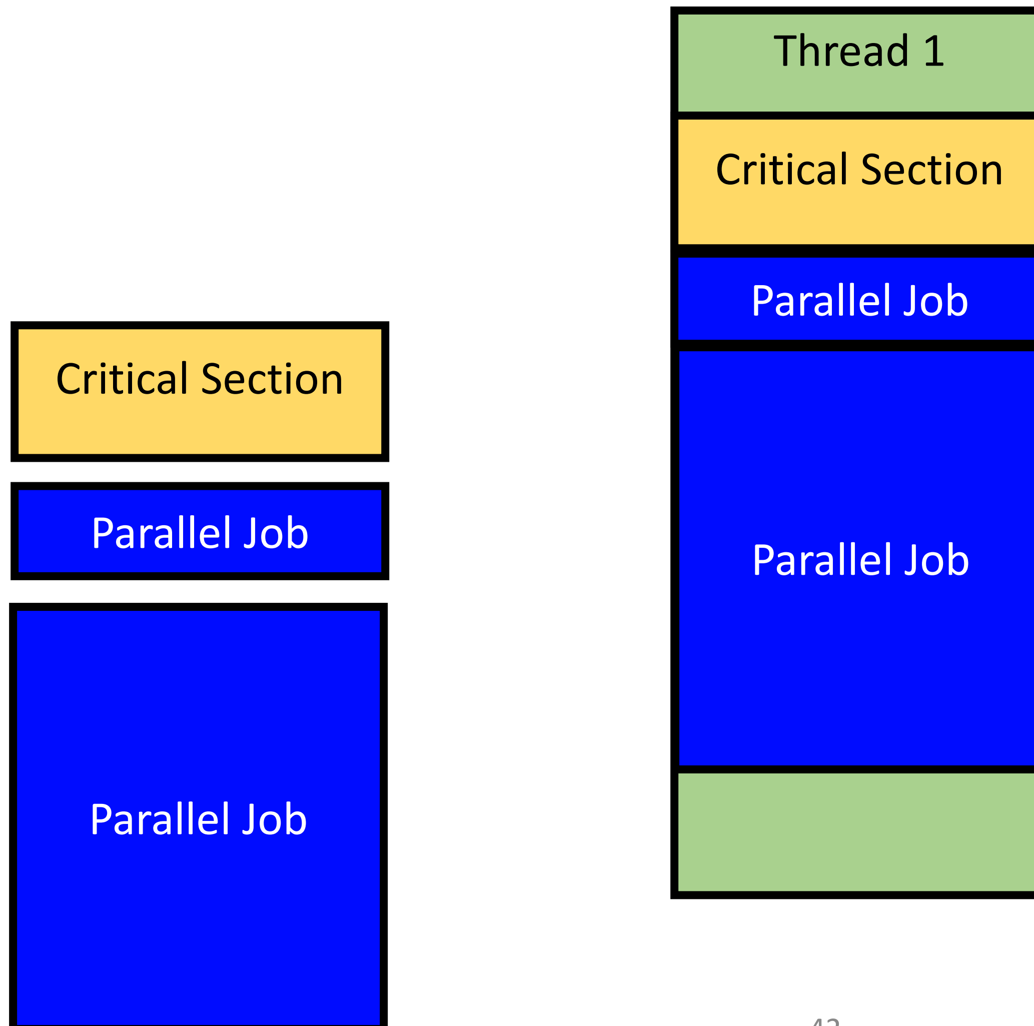

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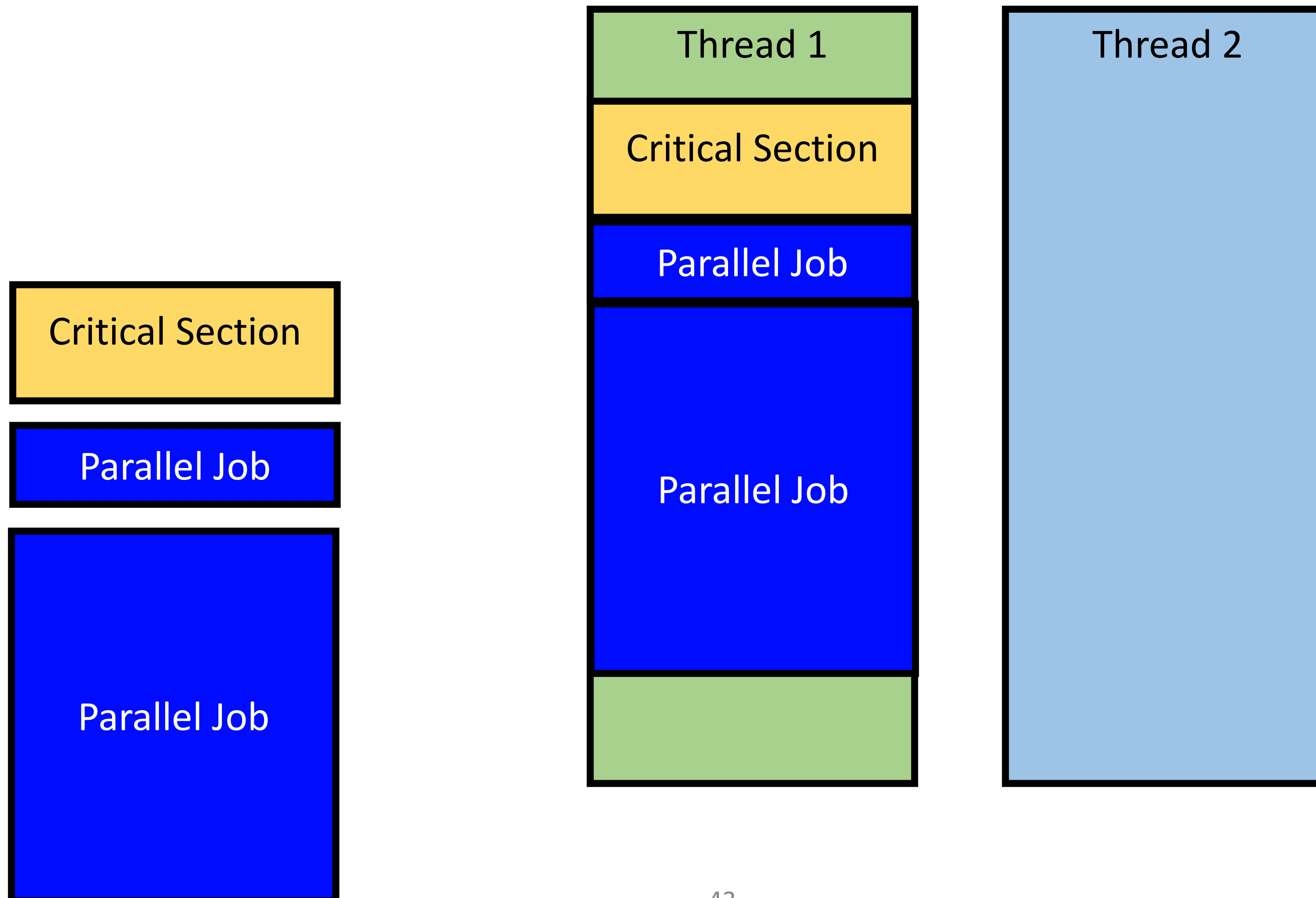

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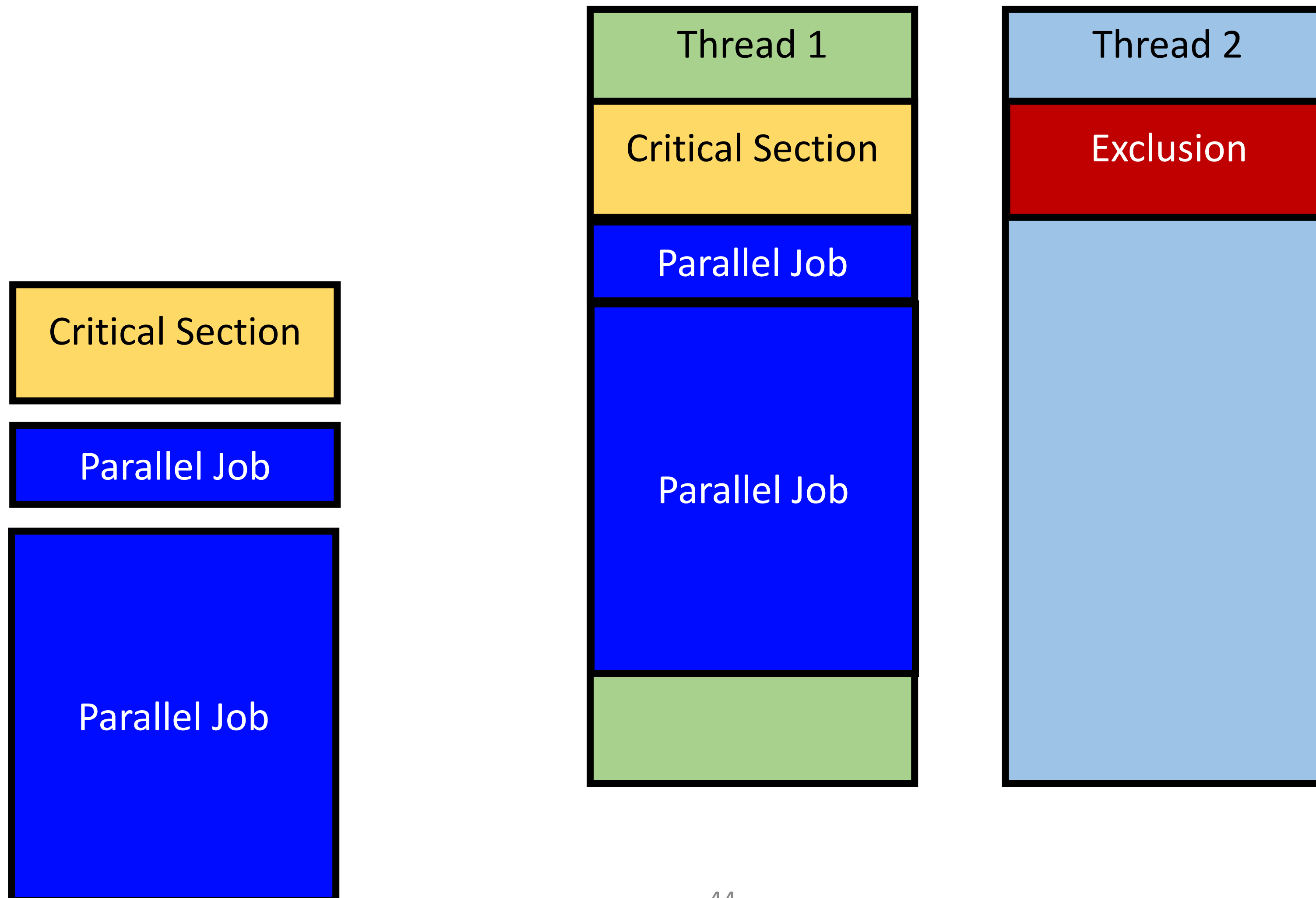

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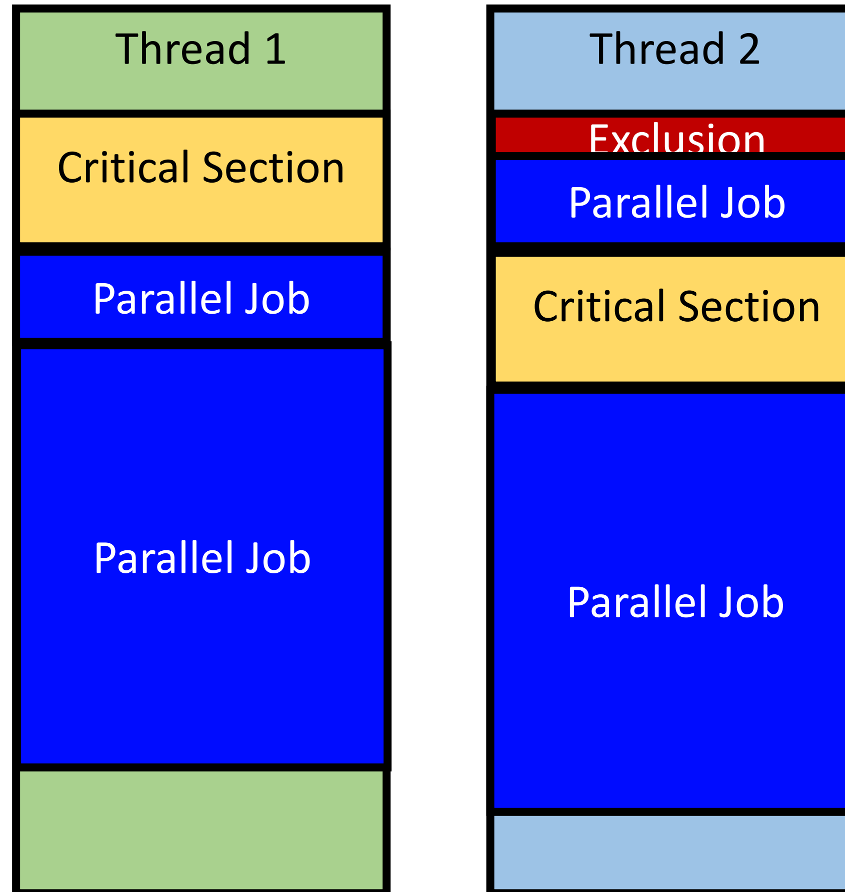

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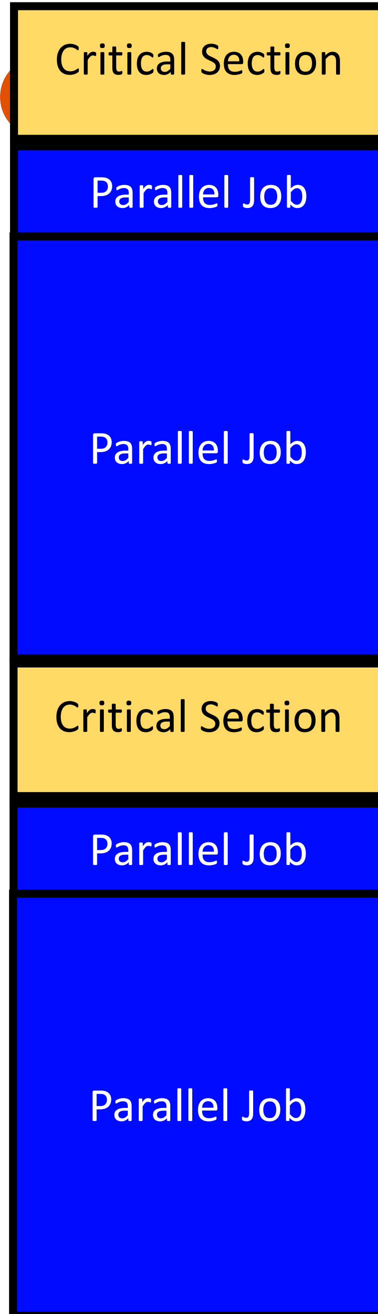
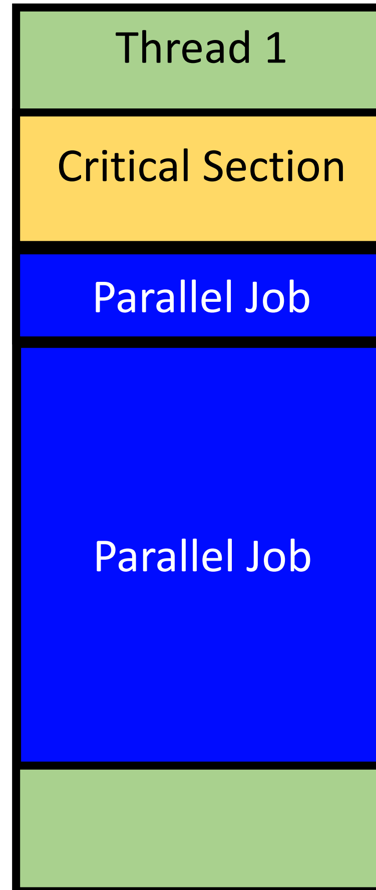
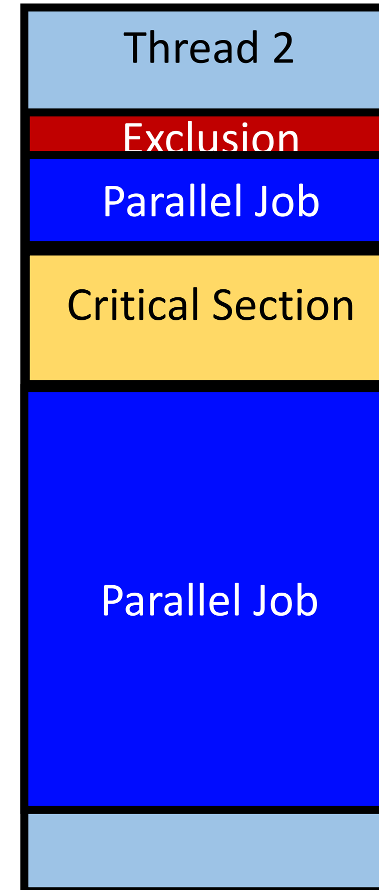






Caveat: Apply Mutex only if required

Mutex can synchronize multiple threads and yield **consistent results**	Making entire program a critical section is **meaningless for parallelism**	Apply critical section **as short as possible**
• No read before previous thread stores shared data	• Running time will be same as single-threaded execution	• maximize benefit of having concurrency • Non-critical sections will run concurrently!

Enabling Mutual Exclusion

- `cli`, in a single processor computer
  - Clear interrupt bit
- CPU will never get interrupt until it runs `sti`
  - Set interrupt bit
- There will be no other execution
  - Any problems?
  - Multi CPU?
  - **`cli/sti` available in Ring 0**

- counter += value
  - **`cli`**
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
  - **`sti`**

Mutex (Mutual Exclusion)

- Lock
  - Prevent others enter the critical section
- Unlock
  - Release the lock, let others acquire the lock

- counter += value
  - **`lock()`**
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
  - **`unlock()`**

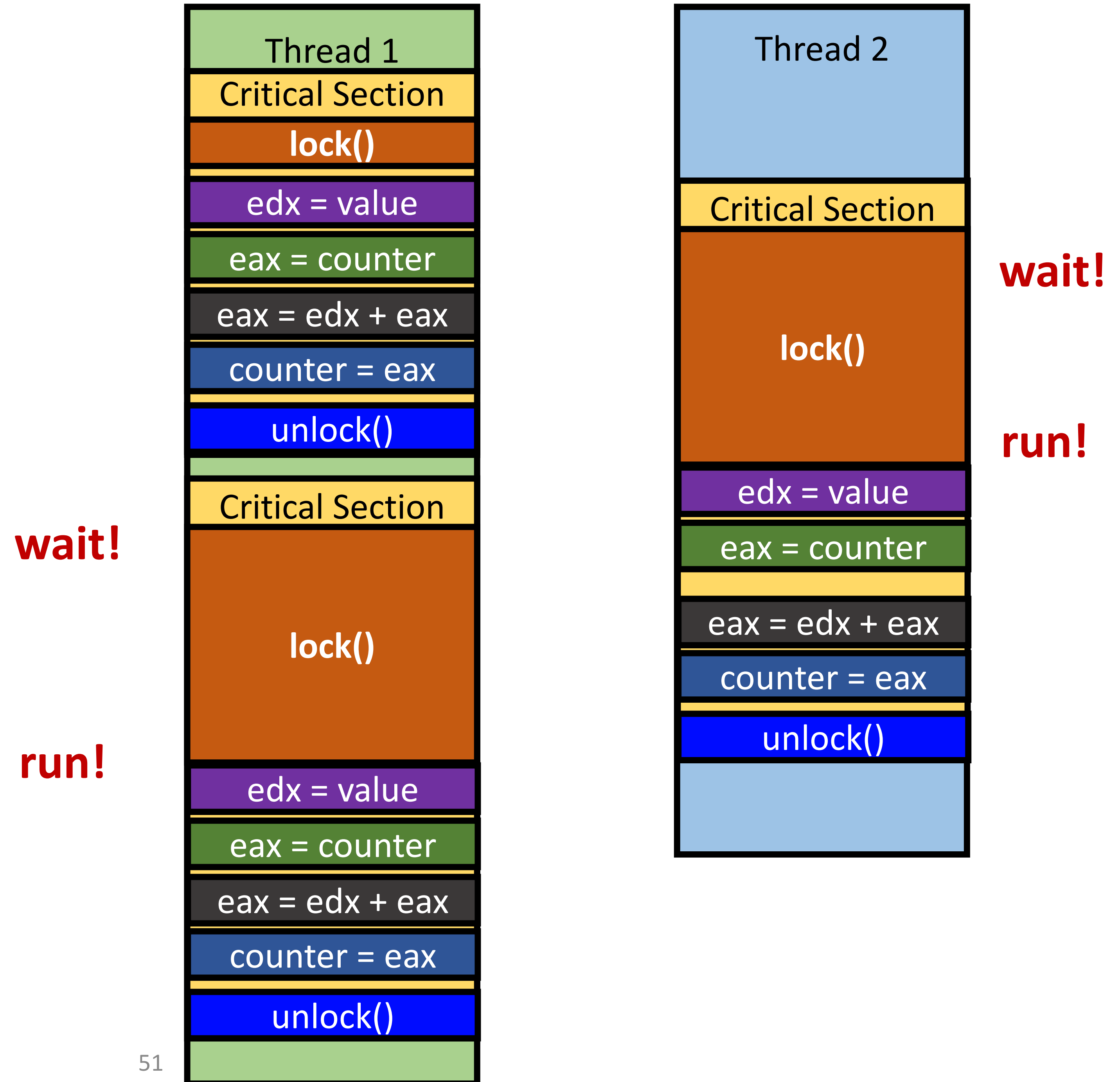
Mutex (Mutual Exclusion)

- **Lock** → prevent others from entering critical section

- How?
  - Check if any other execution in the critical section
    - If it is, wait; busy-waiting with while()
  - If not, **acquire the lock**!
    - Others cannot get into the critical section
  - Run critical section
  - Unlock, let other execution know that I am out!

- counter += value
  - **`lock()`**
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
  - **`unlock()`**

Mutex Example



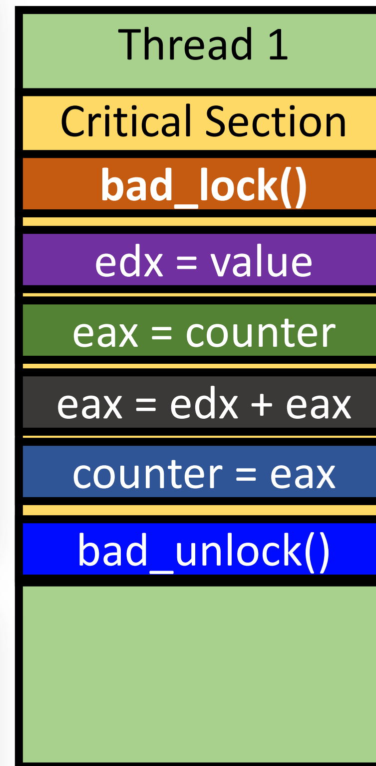
How Can We Implement Locks?

```
void
bad_lock(volatile uint32_t *lock) {
    while (*lock == 1);
    *lock = 1;
}

void
bad_unlock(volatile uint32_t *lock) {
    *lock = 0;
}
```

```
void *
count_bad_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        bad_lock(&lock);
        count += 1;
        bad_unlock(&lock);
    }
}
```

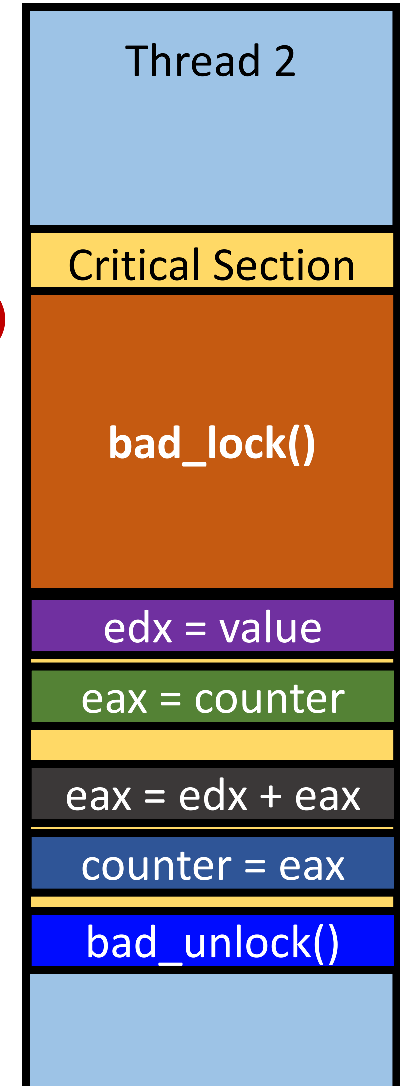
Critical Section



*lock == 0, pass while
*lock = 1 (T1)

*lock == 1, stay in while (T2)

*lock = 0 (T1)
*lock == 0, break while (T2)
*lock = 1 (T2)



Unfortunately, only works in single CPU environment

Summary

- Single-threaded CPU performance does not increase linearly anymore
  - CPU contains many cores to speed up by concurrent execution

- Process and Thread are two options for exploiting concurrency
  - Process: new page directory/table; do not share memory; isolated
  - Thread: shares CR3 (page directory/table); shared memory; not isolated

- Data race could happen if two or more threads access same memory
  - Mutex is one way of avoiding this