K22 - Operating Systems: Design Principles and Internals

Fall 2025 @dit

Vaggelis Atlidakis

Lecture 11

References: Similar OS courses @Columbia, @Stanford, @UC San Diego, @Brown, @di (previous years); and textbooks: Operating Systems: Three Easy Pieces, Operating Systems: Principles and Practice, Operating System Concepts, Linux Kernel Development, Understanding the Linux Kernel

Overview

- We'll start from hardware and follow a question-oriented approach
    - ~~Intro [Q: What is an OS?]~~
    - ~~Events [Q: When does the OS run?]~~
    - ~~Runtime [Q: How does a program look like in memory?]~~
    - ~~Processes [Q: What is a process?]~~
    - ~~IPC [Q: How do processes communicate?]~~
    - ~~Threads [Q: What is a thread?]~~
    - Synchronization [Q: What goes wrong w/o synchronization?]
    - Time Management [Q: What is scheduling?]
    - Memory Management [Q: What is virtual memory?]
    - Files [Q: What is a file descriptor?]
    - Storage Management [Q: How do we allocate disk space to files?]

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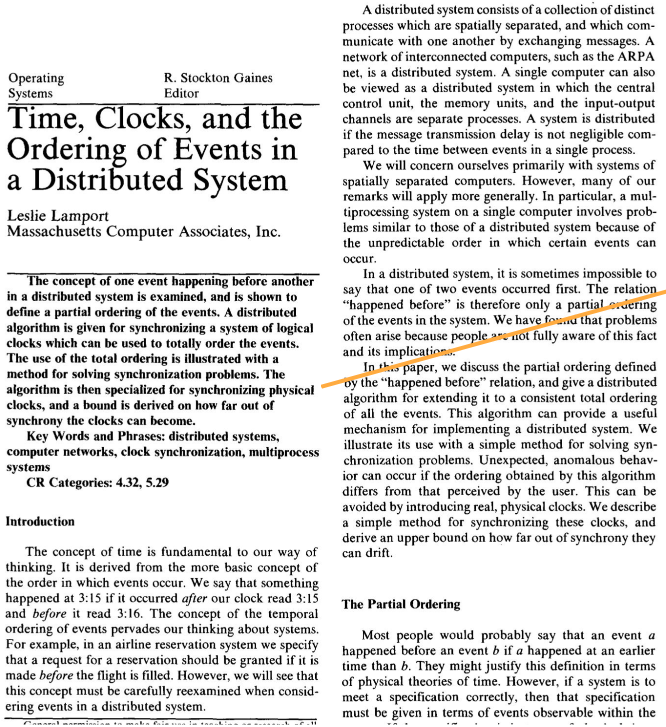
* Basic (H/W & S/W)
* Abstractions
* Primitives
* Mechanisms

Necessary glossary to talk about *synchronization*

- **Parallel operations:** Operations that are happening at the same time, on different processors
- **Concurrent operations:** Operations that are happening in overlapping time intervals, seemingly simultaneously
- **Interleaving of execution:** The order with which concurrent operations are scheduled in for and out of execution
- **Happens-before relationship:** A *partial ordering* of concurrent operations of a program
- **Sequential consistency:** The result of any execution of concurrent operations is the same as if all operations on all processors were executed in some sequential (global) order, and the operations of each individual processor appear in this sequence in the order specified by its program

"happens before" on distributed systems


Operating Systems

R. Stockton Gaines Editor

Time, Clocks, and the Ordering of Events in a Distributed System

Leslie Lamport
Massachusetts Computer Associates, Inc.

The concept of one event happening before another in a distributed system is examined, and is shown to define a partial ordering of the events. A distributed algorithm is given for synchronizing a system of logical clocks which can be used to totally order the events. The use of the total ordering is illustrated with a method for solving synchronization problems. The algorithm is then specialized for synchronizing physical clocks, and a bound is derived on how far out of synchrony the clocks can become.

Key Words and Phrases: distributed systems, computer networks, clock synchronization, multiprocess systems

CR Categories: 4.32, 5.29

Introduction

The concept of time is fundamental to our way of thinking. It is derived from the more basic concept of the order in which events occur. We say that something happened at 3:15 if it occurred *after* our clock read 3:15 and *before* it read 3:16. The concept of the temporal ordering of events pervades our thinking about systems. For example, in an airline reservation system we specify that a request for a reservation should be granted if it is made *before* the flight is filled. However, we will see that this concept must be carefully reexamined when considering events in a distributed system.

A distributed system consists of a collection of distinct processes which are spatially separated, and which communicate with one another by exchanging messages. A network of interconnected computers, such as the ARPA net, is a distributed system. A single computer can also be viewed as a distributed system in which the central control unit, the memory units, and the input-output channels are separate processes. A system is distributed if the message transmission delay is not negligible compared to the time between events in a single process.

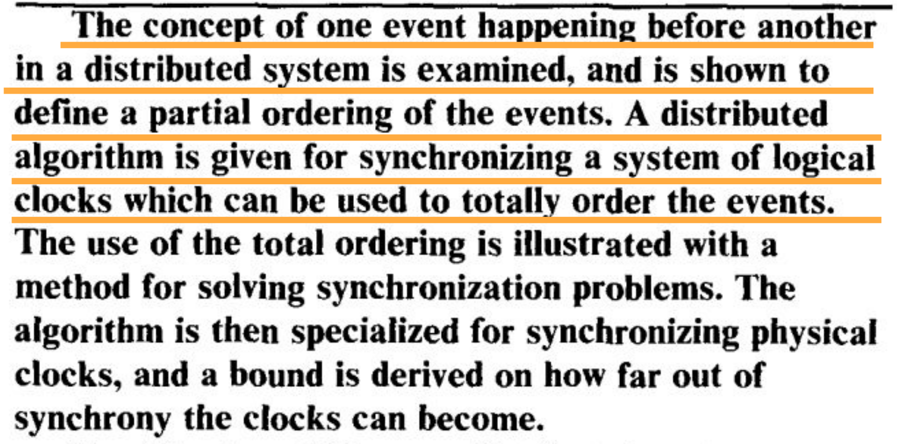
We will concern ourselves primarily with systems of spatially separated computers. However, many of our remarks will apply more generally. In particular, a multiprocessing system on a single computer involves problems similar to those of a distributed system because of the unpredictable order in which certain events can occur.

In a distributed system, it is sometimes impossible to say that one of two events occurred first. The relation "happened before" is therefore only a partial ordering of the events in the system. We have found that problems often arise because people are not fully aware of this fact and its implications.

In this paper, we discuss the partial ordering defined by the "happened before" relation, and give a distributed algorithm for extending it to a consistent total ordering of all the events. This algorithm can provide a useful mechanism for implementing a distributed system. We illustrate its use with a simple method for solving synchronization problems. Unexpected, anomalous behavior can occur if the ordering obtained by this algorithm differs from that perceived by the user. This can be avoided by introducing real, physical clocks. We describe a simple method for synchronizing these clocks, and derive an upper bound on how far out of synchrony they can drift.

The Partial Ordering

Most people would probably say that an event *a* happened before an event *b* if *a* happened at an earlier time than *b*. They might justify this definition in terms of physical theories of time. However, if a system is to meet a specification correctly, then that specification must be given in terms of events observable within the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> [Time, Clocks, and the Ordering of Events in a Distributed System](), 1978, by Leslie Lamport

Partial ordering of concurrent operations

> Logical clocks allows us to define a partial ordering of concurrent operations on a multiprocessor system

> Synchronization is used to enforce that a partial order of concurrent operations (i.e., some "happens-before" relationship) exists

Given two concurrent operations p1, p2
with a "dependency" such that p1 must always "happen before" p2,
synchronization mandates that $t1(i) < t2(i)$ $\forall$ $i \in [1, n]$, where
 $t1(i)$ is the time when p1 ends its i-th execution
 $t2(i)$ is the time when p2 starts its i-th execution

Reasoning about sequential consistency

How to Make a Multiprocessor Computer That Correctly Executes Multiprocess Programs

LESLIE LAMPORT

***Abstract*—Many large sequential computers execute operations in a different order than is specified by the program. A correct execution is achieved if the results produced are the same as would be produced by executing the program steps in order. For a multiprocessor computer, such a correct execution by each processor does not guarantee the correct execution of the entire program. Additional conditions are given which do guarantee that a computer correctly executes multiprocess programs.**

***Index Terms*—Computer design, concurrent computing, hardware correctness, multiprocessing, parallel processing.**

A high-speed processor may execute operations in a different order than is specified by the program. The correctness of the execution is guaranteed if the processor satisfies the following condition: the result of an execution is the same as if the operations had been executed in the order specified by the program. A processor satisfying this condition will be called *sequential*. Consider a computer composed of several such processors accessing a common memory. The customary approach to designing and proving the correctness of multiprocess algorithms [1]–[3] for such a computer assumes that the following condition is satisfied: the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the

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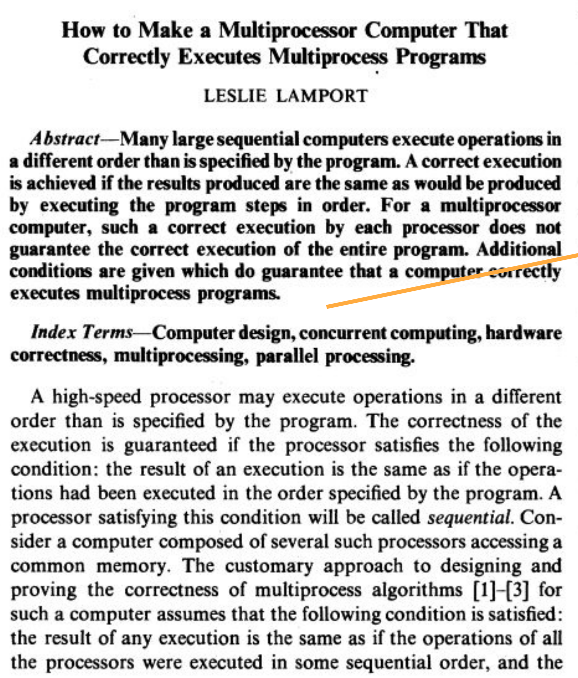
Reasoning about sequential consistency



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"Problems" due to lack of synchronization

> Race conditions: A timing dependent error involving shared state which occurs when the interleaving of execution of concurrent operations leads to erroneous program behaviour

> **Reasons for race conditions:**

- Data races: Non-atomic, unsynchronized, concurrent operations, at least one of which mutating shared state
- Semantic ordering errors: Code that does not enforce the order programmers intended to for a group of memory accesses
- Weak memory consistency models: The set of allowed behaviours w.r.t. memory operation is not what the programer expected

What is so hard about correct concurrent code?

> Concurrent progs have too many execution interleavings

- Too many ways something erroneous could happen
- Need to explore an enormous state space

> Correctness needs a definite and **complete** answer

- Inspected 100% of the state space ⇒ Can make an assessment
- Inspect 99.9% of the state space ⇒ Can't make any assessment

How many is "too many"?

> Different schedules for four operations P1, P2, P3, and P4, which run in total 11 time quanta; and where

- P1 runs 1 time
- P2 runs 4 times
- P3 runs 4 times
- P4 runs 2 times

> How many different scheduler plans do we need to inspect, to cover the complete state space of possible interleavings? **34,650**

* Trivial example in terms of no of operations
  - **We are not considering myriads of async events**
  - **Yet's it's already too difficult**

A few dedicates of state space exploration

› We' ve been searching for decades ways to reduce the size of the state space of concurrent programs and test them

- Partial-Order Methods for the Verification of Concurrent Systems, in 1995, by Patrice Godefroid.
- Model checking to find serious file system errors, in 2006, by Junfeng Yang et al.
- RESTler: Stateful REST API Fuzzing, in 2019, by Atlidakis et al.

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Data races

- A program contains a data race iif two or more threads
  (1) access the same memory location concurrently
  AND (2) at least one of these accesses is a write
  AND (3) at least one of the accesses is not atomic
  AND (4) neither happens before the other

Such data races may result in undefined program behavior and may lead to unforeseen errors at runtime

- See the ISO/IEC 9899:2011(C11), Sec.-5.1.2.4/25, on multi-threaded executions and data races

Data races

```c
int total = 0;

void *add(void *arg) {
  for (int i = 0; i < 1e6; ++i)
    ++total;
  return NULL;
}

void main() {
  pthread_t t1, t2;

  pthread_create(&t1, NULL, add, (void *) NULL);
  pthread_create(&t2, NULL, add, (void *) NULL);
  pthread_join(t1, NULL);
  pthread_join(t2, NULL);
  printf("Total-1: %d\n", total);

  total = 0;
  pthread_create(&t1, NULL, add, (void *) NULL);
  pthread_join(t1, NULL);
  pthread_create(&t2, NULL, add, (void *) NULL);
  pthread_join(t2, NULL);
  printf("Total-2: %d\n", total);
}
```

```
➜  obdjump -d ./counter

0000000000001159 <add>:

  1159: push %rbp                    # Save base pointer to stack
  115a: mov  %rsp, %rbp              # Set up new stack frame
  115d: mov  %rdi, -0x18(%rbp)       # *arg = %rdi
  1161: movl $0x0, -0x4(%rbp)        # i = 0
  1168: jmp  117d <add+0x24>         # for-loop start

                                          Data race!
  116a: mov  0x2ebc(%rip), %eax      #  %eax ← total
  1170: add  $0x1, %eax              #  %eax += 1
  1173: mov  %eax, 0x2eb3(%rip)      #  total ← %eax

  1179: addl $0x1, -0x4(%rbp)        # i += 1
  117d: cmpl $0xf423f, -0x4(%rbp)    # loop counter compare
  1184: jle  116a <add+0x11>         # for-loop jump
  1186: mov  $0x0, %eax              # rval = %eax
  118b: pop  rbp                     # Restore stack
  118c: ret                          # Return to caller
```

```
➜ git:(master) ✗ ./counter
Total-1: 1011367
Total-2: 2000000

➜ git:(master) ✗ ./counter
Total-1: 1011367
Total-2: 2000000

➜ git:(master) ✗ ./counter
Total-1: 1028085
Total-2: 2000000

➜ git:(master) ✗ ./counter
Total-1: 1011197
Total-2: 2000000

➜ git:(master) ✗ ./counter
Total-1: 1018502
Total-2: 2000000

➜ git:(master) ✗ ./counter
Total-1: 1013853
Total-2: 2000000
```

Data races

> Two domains of state for each thread

- Processor regs (per-thread, local state) vs. Main memory (global state)
- Processor on thread A
  - %reg <- value at main mem. [global vs. local state: consistent]
  - %reg <- %reg + 1 [global vs. local state: divergent]
  - value at main mem. <- %reg [global vs. local state: consistent]
- Thread A gets preempted [shared value at main mem. +1]
- Processor on thread B
  - %reg <- value at main mem. [global vs. local state: consistent]
  - %reg <- %reg + 1 [global vs. local state: divergent]
  - value at main mem. <- %reg [global vs. local state: consistent]
- Thread B gets preempted [shared value at main mem. +1]

OK Interleaving

Data races

> Another execution interleaving

- Processor on thread A
  - %reg <- value at main mem. [global vs. local state: consistent]
- Processor on thread B
  - %reg <- value at main mem. [global vs. local state: consistent]
  - %reg <- %reg + 1 [global vs. local state: divergent]
  - value at main mem. <- %reg [global vs. local state: consistent]
- Processor on thread A
  - **OS job**: Load %reg with its value before ctx switch
  - Thread A "thinks" %reg ⇔ shared value at main mem.
  - **But**: shared value has been mutated by someone else

NOT OK
Interleaving

Data races

> Yet, another execution interleaving

- Processor on thread B
  - %reg <- value at main mem. [global vs. local state: consistent]
- Processor on thread A
  - %reg <- value at main mem. [global vs. local state: consistent]
  - %reg <- %reg + 1 [global vs. local state: divergent]
  - value at main mem. <- %reg [global vs. local state: consistent]
- Processor on thread B
  - **OS job**: Load %reg with its value before ctx switch
  - Thread B "thinks" %reg ⇔ shared value at main mem.
  - **But**: shared value has been mutated by someone else

NOT OK Interleaving

Data races

- **Bottom-line**: Concurrent writes on shared state?
  - Each thread must finish its business before it gets preempted
  - Inseparable "instructions" ⇒ **Atomic operations**

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Semantic ordering errors: Benign

```c
void* func1(void* arg) {
  printf("1\n");
  return NULL;
}
void* func2(void* arg) {
  printf("2\n");
  return NULL;
}
int main(void) {
  pthread_t t1, t2;

  pthread_create(&t1, NULL, func1, NULL);
  pthread_create(&t2, NULL, func2, NULL);

  pthread_join(t1, NULL);
  pthread_join(t2, NULL);
  return 0;
}
```

```
➜ concurrency git:(master) ✗ ./nosync
1
2

➜ concurrency git:(master) ✗ ./nosync
1
2

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1
2

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1
2
```

Semantic ordering errors: Detrimental

```c
int mode = 0;             // 1: Low-power; 2: High-power
int filter_engage = 0;    // 0: Filter not engaged; 1: Filter engaged
int input_finalized = 0;  // Has operator finished input?

void *filter_control(void *arg) {
  while (!input_finalized) {
    sched_yield();
  }
  usleep(100);
  if (mode == 2)
    filter_engage = 1;
  else
    filter_engage = 0;
  return NULL;
}

void beam_activate() {
  if (mode == 2 && filter_engage == 0)
    printf("🚨 Treatment with high-power beam and no filter in place\n");
  else
    printf("🟢 Safe setup\n");
}

int main(void) {
  pthread_t filter_control_t;
  pthread_create(&filter_control_t, NULL, filter_control, NULL);
  usleep(100);  // Time window 1:  operator does  initial setup
  mode = 1;
  input_finalized = 1;
  usleep(100); // Time window 2: operator does  final edits
  mode = 2;
  pthread_join(filter_control_t, NULL); // Control logic completed
  beam_activate();
}
```

```
➜ concurrency git:(master) ✗ ./therac25
🟢 Safe setup.
➜ concurrency git:(master) ✗ ./therac25
🟢 Safe setup.
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🟢 Safe setup.
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🟢 Safe setup.
➜ concurrency git:(master) ✗ ./therac25
🚨 Treatment with high-power beam and no filter in place :-(
```

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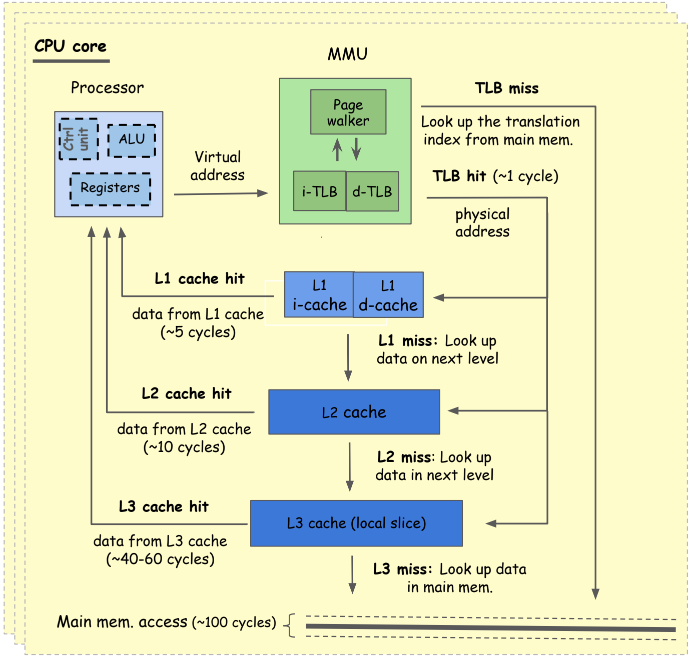
Relaxing sequential consistency

- **Sequential consistency:** Every load from a memory address gets its value from the last store before it to the same address in **global memory**



> Easy to reason / Impractically slow

- The effects of each instruction must be visible on all cores before starting the next instruction

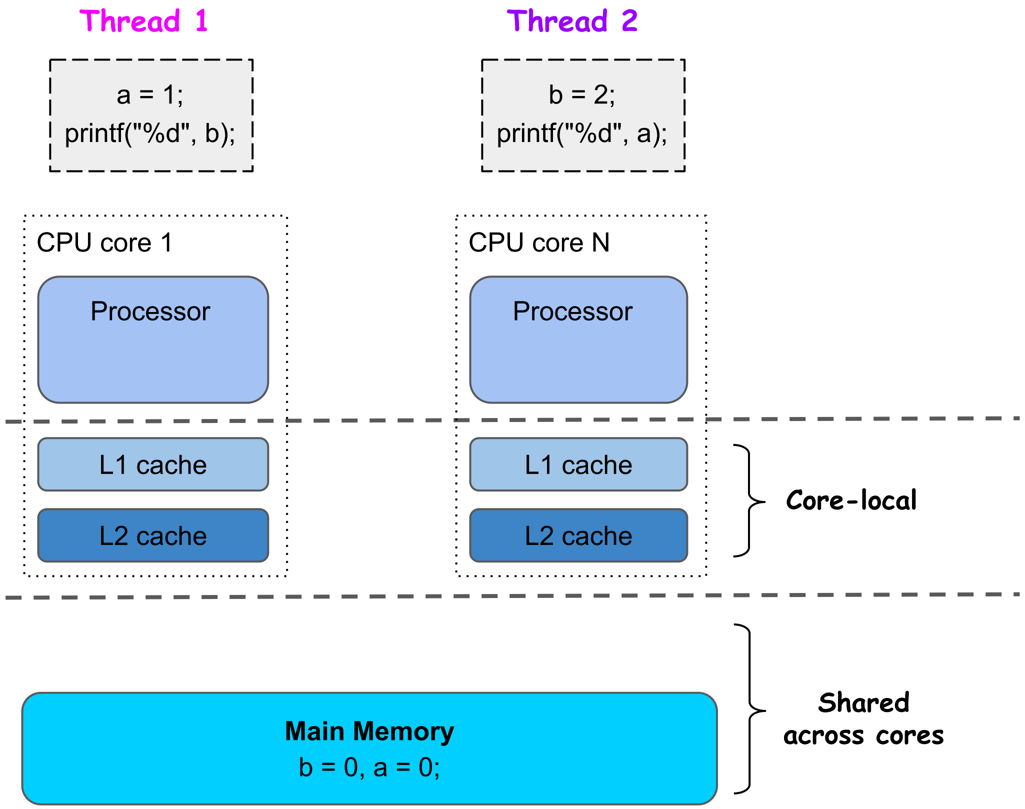
- The first level of "global" memory is the L3 cache with an overhead of at least 40 cycles for access time

- **In practice: We relax the memory consistency model to hide write latency and avoid processor stalls**

Relaxing sequential consistency

- **x86 Total Store Order (TSO)**
  - "Stores" are ordered between cores
  - "Store-Load" pairs can be reordered between cores
- **Why?** Need to avoid store latency
  - Before committing data on a core-local cache line (L1 or L2 cache), a core must wait for the cache lines to be invalidated on all other cores
  - The hardware does this via cache coherency protocols
  - Latency of store instructions even on core-local mem. references
- Solution
  - Use of processor-internal write buffers to hide store latency
  - Memory model violates sequential consistency
  - Reorderings of operations ⇒ Potential for unexpected program behaviour

Assume SC - Can this program print "00"?

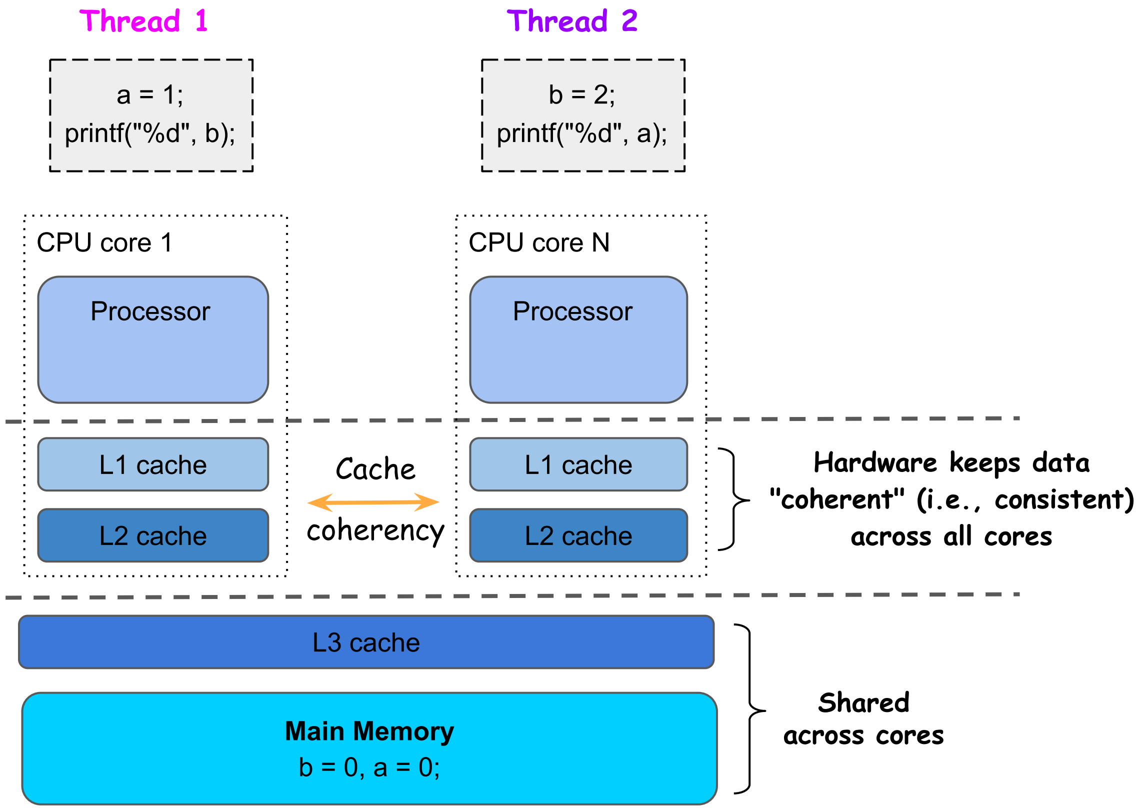


Sequential consistency: Reminder

Pragmatic explanation

- Processors issue loads and stores in their local memory respecting their local program order
- Every load from a memory address gets its value from the last store before it, on the same memory address, in global memory

x86 Total Store Order (TSO)



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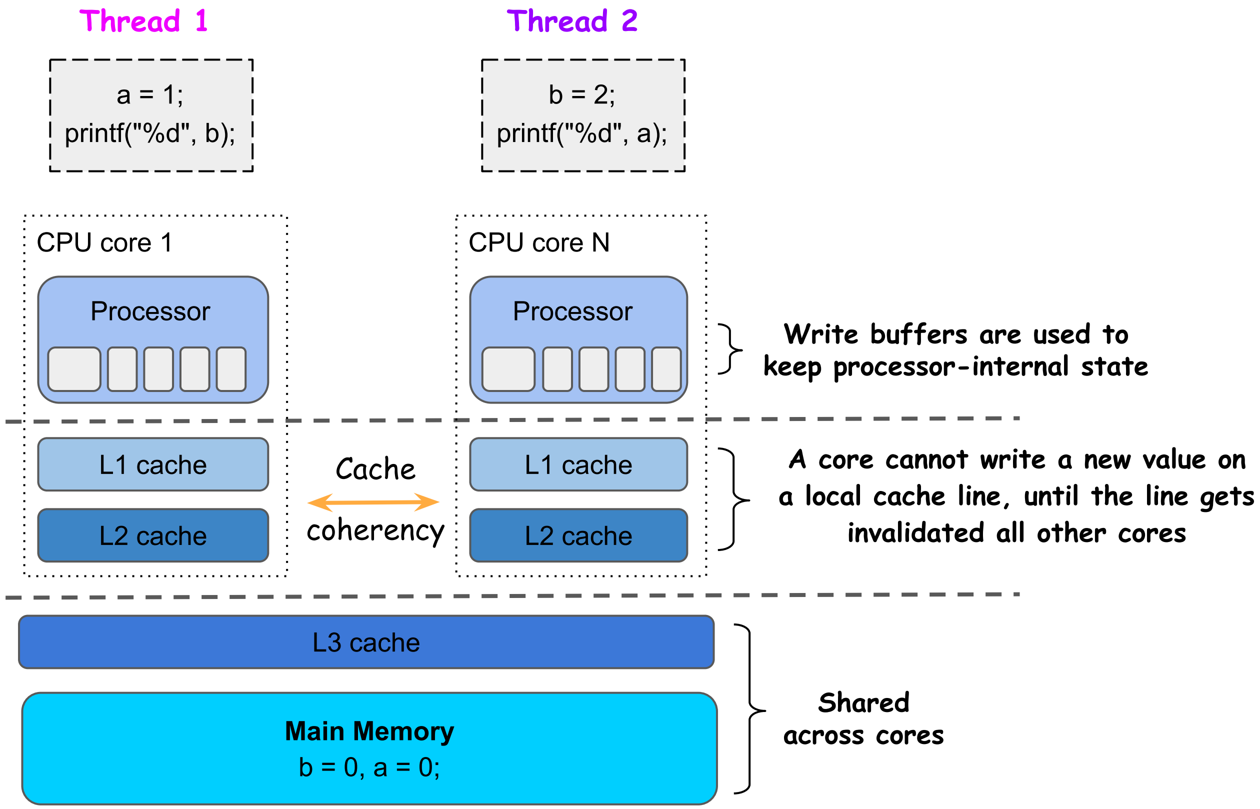

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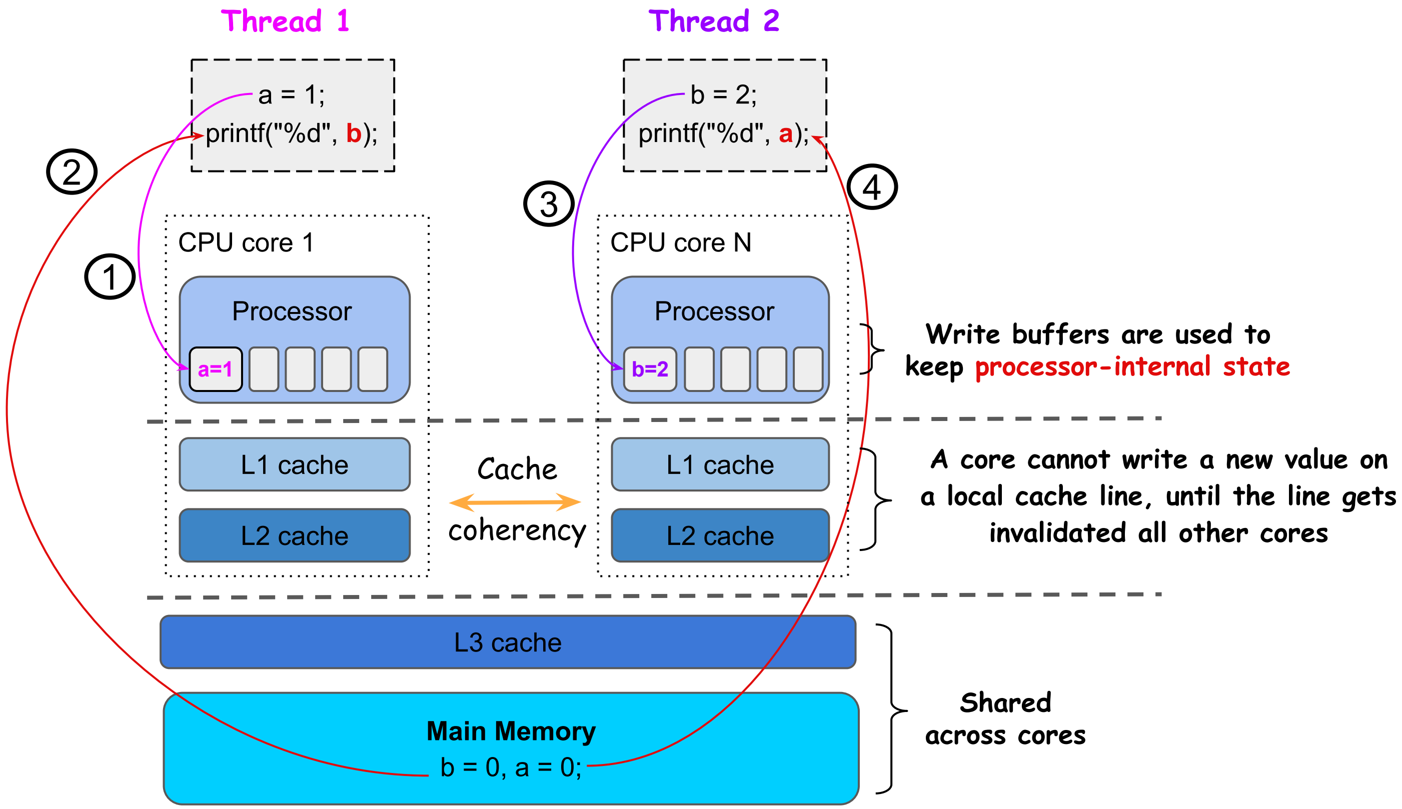

How to prevent race conditions

> **Solutions**

- re:: Data races: Disable preemption (s/w)? Atomicity (h/w)?

>> Atomicity hits data races on their head **by definition**

>> "Relaxing" synchronization: "<u>a</u> happens before" ⇒ "<u>some</u> happens before"

- Processor on thread A
  - %reg <- value at main mem. [global vs. local state: consistent]
  - %reg <- %reg + 1 [global vs. local state: divergent]
  - value at main mem. <- %reg [global vs. local state: consistent]

Have h/w execute these "inseparable" instructions in one go?

- Processor on thread B
  - %reg <- value at main mem. [global vs. local state: consistent]
  - %reg <- %reg + 1 [global vs. local state: divergent]
  - value at main mem. <- %reg [global vs. local state: consistent]

Have h/w execute these "inseparable" instructions in one go?

How to prevent race conditions

- Solutions
  - re:: Data races: Disable preemption (s/w)? Atomicity (h/w)?
  - re:: Semantic ordering errors: h/w guardrails? Verification?
  - re:: Weak memory consistency models: Memory barriers
- Looks like we are getting somewhere, but…
  - What operations can "inseparable" instructions express?

Step back on the big picture

> **What are we trying to achieve?** Ensure the execution interleaving of concurrent operations does not lead to unforeseen, erroneous program behavior at runtime

- Looks like we are getting somewhere, but...
  > What operations can "inseparable" instructions express?

    - %reg <- value at main mem.
    - %reg <- %reg + 1
    - value at main mem. <- %reg

  > Too primitive ⇒ Well... use it as primitive...

Step back on the big picture

- **Where we are?** Solved most of the **evils** we've seen so far
  - **Memory barriers** => Prevent reorderings
  - **Atomicity** => Some "happens-before" => Enough for data races
    - Atomic instructions only express too primitive operations
    - Need atomicity of composite operations
    - **Ideally:** atomicity of arbitrary many instructions

- Arbitrary many instructions ⇒ Critical Section
- Atomicity of arbitrary instructions ⇒ Mutual exclusion

The Critical Section (CS) problem

- ***Critical section*** (tangible set)
  - A sequence of instructions operating on shared state that ought to be executed by one thread at a time
- ***Mutual exclusion*** *(conceptual property)*
  - If I do, you wait; If you do, I wait...
  - **More generally:** At most one does at a time, all others wait
- ***The critical section problem***
  - How to allow only one thread at a time in a cs?
  - Rephrase: How to turn a sequence of instructions into an "atomic block"?
  - Rephrase: How to restrict the interleavings of thread executions re: entering the cs? (some happens-before relationship exists)

Designing a solution to the CS problem

- Correctness properties (non-negotiable)
  - Mutual exclusion: At most one thread inside the CS at any time
  - Progress: If multiple threads attempt to enter the CS, one must be allowed to proceed (a.k.a. liveness)
  - Starvation-free: If a thread is waiting to enter the CS, it must eventually enter (a.k.a. bounded-wait)
- Efficiency and Fairness properties (good to have)
  - Resource-efficiency: Don't waste processor cycles while waiting (busy-waiting) to enter the CS; voluntarily yield the processor
  - Fairness: All threads must wait approximately the same amount of time outside of the CS

Synchronized access to CS with locking

> We have reached our destination!

- Divide code in two parts
  - CS: Executed with serialized access on some partial order
  - Code outside CS: Executed concurrently without any concerns
- Synchronized access to critical sections
- Coordinate among threads to restrict the possible interleavings
- How? **Locks/Locking**

Implementing locks

> **Lock:** A token-like synchronization primitive used to coordinate concurrent thread accesses on CS

- While a thread cannot acquire the **lock**, it waits outside of the CS until it acquires the **lock**
- When a thread acquires the **lock**, it execute instructions inside the cs, while all other threads wait outside the CS
- When a thread finishes executing instructions inside the CS, it releases the **lock** and any thread can acquire it

Draft API for locks

- Initialize an **shared** (noun: lock) variable
  >> Prototype: void **init**(lock_type *lock_ptr);

- Acquire (verb: lock) the (noun: lock) variable
  >> Prototype: void **lock**(lock_type *lock_ptr);

- Release (verb: unlock) the (noun: lock) variable
  >> Prototype: void **unlock**(lock_type *lock_ptr);

Blast from the past

```c
int total = 0;

void *add(void *arg) {

 for (int i = 0; i < 1e6; ++i) {
  pthread_mutex_lock(&l);
  ++total;
  pthread_mutex_unlock(&l);
 }

 return NULL;
}

void main() {
 pthread_t t1, t2;

 pthread_create(&t1, NULL, add, (void *) NULL);
 pthread_create(&t2, NULL, add, (void *) NULL);
 pthread_join(t1, NULL);
 pthread_join(t2, NULL);
 printf("Total-1: %d\n", total);

 total = 0;
 pthread_create(&t1, NULL, add, (void *) NULL);
 pthread_join(t1, NULL);
 pthread_create(&t2, NULL, add, (void *) NULL);
 pthread_join(t2, NULL);
 printf("Total-2: %d\n", total);
}
```

```
➜  obdjump -d ./counter

0000000000001159 <add>:
  1159: push %rbp                  # Save base pointer to stack
  115a: mov  %rsp, %rbp            # Set up new stack frame
  115d: mov  %rdi, -0x18(%rbp)     # *arg = %rdi
  1161: movl $0x0, -0x4(%rbp)      # i = 0
  1168: jmp  117d <add+0x24>       # for-loop start
..........................................................
  118e: lea   0x2eeb(%rip),%rax
  1195: mov   %rax,%rdi                                 } lock  the lock
  1198: call  1070 <pthread_mutex_lock@plt>
..........................................................
  116a: mov  0x2ebc(%rip), %eax    #  %eax ← total
  1170: add  $0x1, %eax            #  %eax += 1         } Critical section
  1173: mov  %eax, 0x2eb3(%rip)    #  total ← %eax
..........................................................
  11ac:  lea   0x2ecd(%rip),%rax
  11b3:  mov   %rax,%rdi                                } Unlock the lock
  11b6:  call  1040 <pthread_mutex_unlock@plt>
..........................................................
  1179: addl $0x1, -0x4(%rbp)      # i += 1
  117d: cmpl $0xf423f, -0x4(%rbp)  # loop counter compare
  1184: jle  116a <add+0x11>       # for-loop jump
  1186: mov  $0x0, %eax            # rval = %eax
  118b: pop  rbp                   # Restore stack
  118c: ret                        # Return to caller
```

Blast from the past

> Yet, another execution interleaving

- Processor on thread B
  - %reg <- value at main mem. [global vs. local state: consistent]
- Processor on thread A
  - %reg <- value at main mem. [global vs. local state: consistent]
  - %reg <- %reg + 1 [global vs. local state: divergent]
  - value at main mem. <- %reg [global vs. local state: consistent]
- Processor on thread B
  - **OS job**: Load %reg with its value before ctx switch
  - Thead B "thinks" %reg ⇔ shared value at main mem.
  - **But**: shared value has been mutated by someone else

Cannot happen

Uniprocessor lock (CONFIG_SMP=off, CONFIG_PREEMPT=off)

```
>> typedef uint8_t raw_spinlock_t;
>> void init(raw_spinlock_t *lock) {
        *lock = 0; // 0 = unlocked, 1 = locked
   }
>> void lock(raw_spinlock_t *lock) {
        return;
   }
>> void unlock(raw_spinlock_t *lock) {
        return;
   }
```

Uniprocessor lock (CONFIG_SMP=off, CONFIG_PREEMPT=on)

```
>> typedef uint8_t raw_spinlock_t;
>> void init(raw_spinlock_t *lock) {
           *lock = 0; // 0 = unlocked, 1 = locked
   }
>> void lock(raw_spinlock_t *lock) {
           disable_preemption();
    }
>> void unlock(raw_spinlock_t *lock) {
           enable_preemption();
    }
```

Another blast from the past

> What operations can "inseparable" instructions express?

- %reg <- [mem.]
- %reg <- %reg + 1
- [mem.] <- %reg

Atomic operation

Another blast from the past

> Consider another atomic operation

xchgb reg, [mem] (composite operation / "inseparable" instructions)

- temp <- %reg1
- %reg1 <- [mem.]
- [mem.] <- temp

Atomic swap (exchange): [mem] <-> %reg

> Why the hassle?

```
uint8_t test_and_set(uint8_t *flag) {
    %reg <- 1               // "set" val of %reg to 1
    xchgb %reg, *flag       // val of reg <->  val of flag
    return %reg             // %reg has the old val of flag
}
```

>> **Return 1?** flag was 1 (**lock was locked**)

>> **Return 0?** flag was 0, and is now 1 (**lock was unlocked and just got locked**)

Draft SMP spinlock implementation

```
>> void init(lock_type *lock_ptr) {
        *lock_ptr = 0; // 0 = unlocked, 1 = locked
   }
>> void lock(lock_type *lock_ptr) {
        preempt_disable();          // don't loose processor, if getting the lock
        while (test_and_set(lock)) ; // try while lock not free
   }
>> void unlock(lock_type *lock_ptr) {
        __asm__ volatile("sfence" ::: "memory"); // mem. barrier
        // all write mem. ops from the cs must completed before this point
        *lock = 0;
        preempt_enable();
   }
```

Designing a solution to the CS problem

- Correctness properties (non-negotiable)
  - Mutual exclusion: At most one thread inside the CS at any time
  - Progress: If multiple threads attempt to enter the CS, one must be allowed to proceed (a.k.a. liveness)
  - Starvation-free: If a thread is waiting to enter the CS, it must eventually enter (a.k.a. bounded-wait)
- Efficiency and Fairness properties (good to have)
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>> Sleeping locks: Self-preempt and sleep if can't acquire the lock

- Do use when: Cost of 2*ctx switch << cost of instruction of cs
- Do use when: Relatively larger CS
- Do NOT use when: In interrupt handlers — Why?
- Known by the name "mutex"

Implementing a sleeping lock

```
typedef struct mutex_t {
  // the "lock" variable
  // initially "unlocked"
  int lock = 0;
  // keeps track of waiters
  queue_t queue = NULL;
} mt;
```

```
void mutex_lock(mutex_t *mt) {
  while (test_and_set(&mt->lock)) {

    // lock is being held
    // register self on waiters
    enqueue(&mt->queue, self);
    // yield the processor
    add_task_to_waitq(self);
  }
}
```

```
void mutex_unlock(mutex_t *mt) {
  // release the lock
  mt->lock = 0
  // let a waiters know
  if (!queue_empty(mt->queue)) {
    wake_up(dequeue(mt->queue))
  }
}
```

Implementing a sleeping lock: Lost wakeup

```c
typedef struct mutex_t {
  // the "lock" variable
  // initially "unlocked"
  int lock = 0;
  // keeps track of waiters
  queue_t queue = NULL;
} mt;
```

```c
void mutex_lock(mutex_t *mt) {
  while (test_and_set(&mt->lock)) {

    // lock is being held
    // register self on waiters
    enqueue(&mt->queue, self);
    // yield the processor
    add_task_to_waitq(self);
  }
}
```

```c
void mutex_unlock(mutex_t *mt) {
  // release the lock
  mt->lock = 0
  // let a waiters know
  if (!queue_empty(mt->queue)) {
    wake_up(dequeue(mt->queue))
  }
}
```

Implementing a sleeping lock

```
typedef struct mutex_t {
  // the "lock" variable
  // initially "unlocked"
  int lock = 0;
  // lock is a shared variable
  raw_spinlock_t guard = 0;
  // keeps track of waiters
  queue_t queue = NULL;
} mt;
```

```
void mutex_lock(mutex_t *mt) {
  spinlock_lock(&mt->guard)
  // lock is being held
  while (mt->lock != 0) {
    // register self on waiters
    enqueue(&mt->queue, self);
    spinlock_unlock(&mt->guard);
    // yield the processor
    add_task_to_waitq(self);
    spinlock_lock(&mt->guard);
  }
  // acquire the lock
  mt->lock = 1;
  spinlock_unlock(&mt->guard);
}
```

```
void mutex_unlock(mutex_t *mt) {
  spinlock_lock(&mt->guard);
  // release the lock
  mt->lock = 0
  // let a waiters know
  if (!queue_empty(mt->queue)) {
    wake_up(dequeue(mt->queue))
  }
  spinlock_unlock(&mt->guard)
}
```

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Understanding contention

>> Random hash-table insertions, 1024 buckets (machine: 12 vCPUs)

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- Synchronization w/ global lock (concurrent, not parallel)

```
void global_insert(int key) {
    idx = hash(key);
    Node *n = malloc(sizeof(Node));
    n->key = key;
    n->next = table[idx].head;
    spinlock_lock(&global_lock);
    table[idx].head = n;
    spinlock_unlock(&global_lock);
}
```

Understanding contention

>> Random hash-table insertions, 1024 buckets (machine: 12 vCPUs)

- Synchronization w/ global lock (concurrent, not parallel)
- Synchronization w/ fine-grained, per-bucket lock (concurrent + parallel)

```
void global_insert(int key) {
    idx = hash(key);
    Node *n = malloc(sizeof(Node));
    n->key = key;
    n->next = table[idx].head;
    spinlock_lock(&global_lock);
    table[idx].head = n;
    spinlock_unlock(&global_lock);
}
```

```
void bucket_insert(int key) {
    idx = hash(key);
    Bucket *b = &table[idx];
    Node *n = malloc(sizeof(Node));
    n->key = key;
    n->next = b->head
    spinlock_lock(&b->lock);
    b->head = n;
    spinlock_unlock(&b->lock);
}
```

Understanding contention

>> Random hash-table insertions, 1024 buckets (machine: 12 vCPUs)
- Synchronization w/ global lock (concurrent, not parallel)
- Synchronization w/ fine-grained, per-bucket lock (concurrent + parallel)
- Lock-free implementation w/ atomics (concurrent + parallel; no lock)

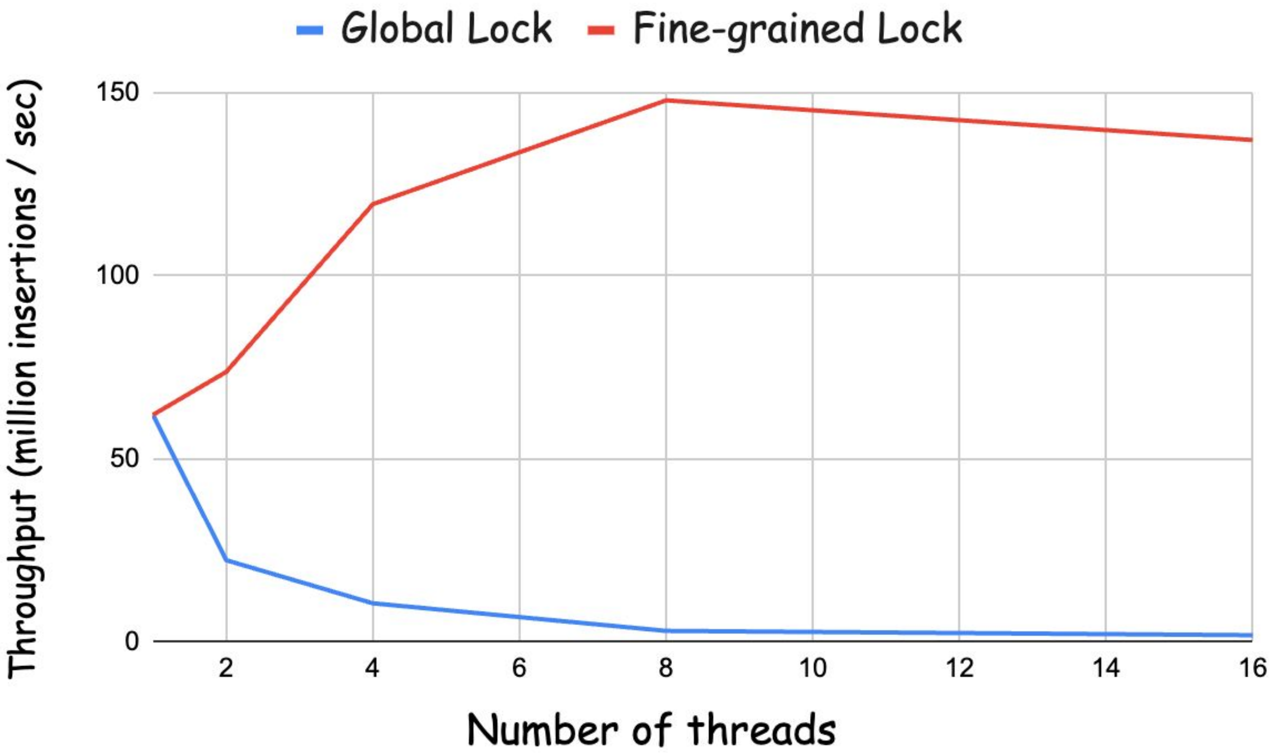
```
void global_insert(int key) {
    idx = hash(key);
    Node *n = malloc(sizeof(Node));
    n->key = key;
    n->next = table[idx].head;
    spinlock_lock(&global_lock);
    table[idx].head = n;
    spinlock_unlock(&global_lock);
}
```

```
void bucket_insert(int key) {
    idx = hash(key);
    Bucket *b = &table[idx];
    Node *n = malloc(sizeof(Node));
    n->key = key;
    n->next = b->head
    spinlock_lock(&b->lock);
    b->head = n;
    spinlock_unlock(&b->lock);
}
```

```
void lockfree_insert(int key) {
    idx = hash(key);
    Bucket *b = &table[idx];
    Node *old_head;
    Node *n = malloc(sizeof(Node));
    n->key = key;
    do {
        old_head = b->head;
        n->next = old_head;
    } while (!cas(&b->head, &old_head, n));
}
```

Understanding contention

>> Random hash-table insertions, 1024 buckets (machine: 12 vCPUs)



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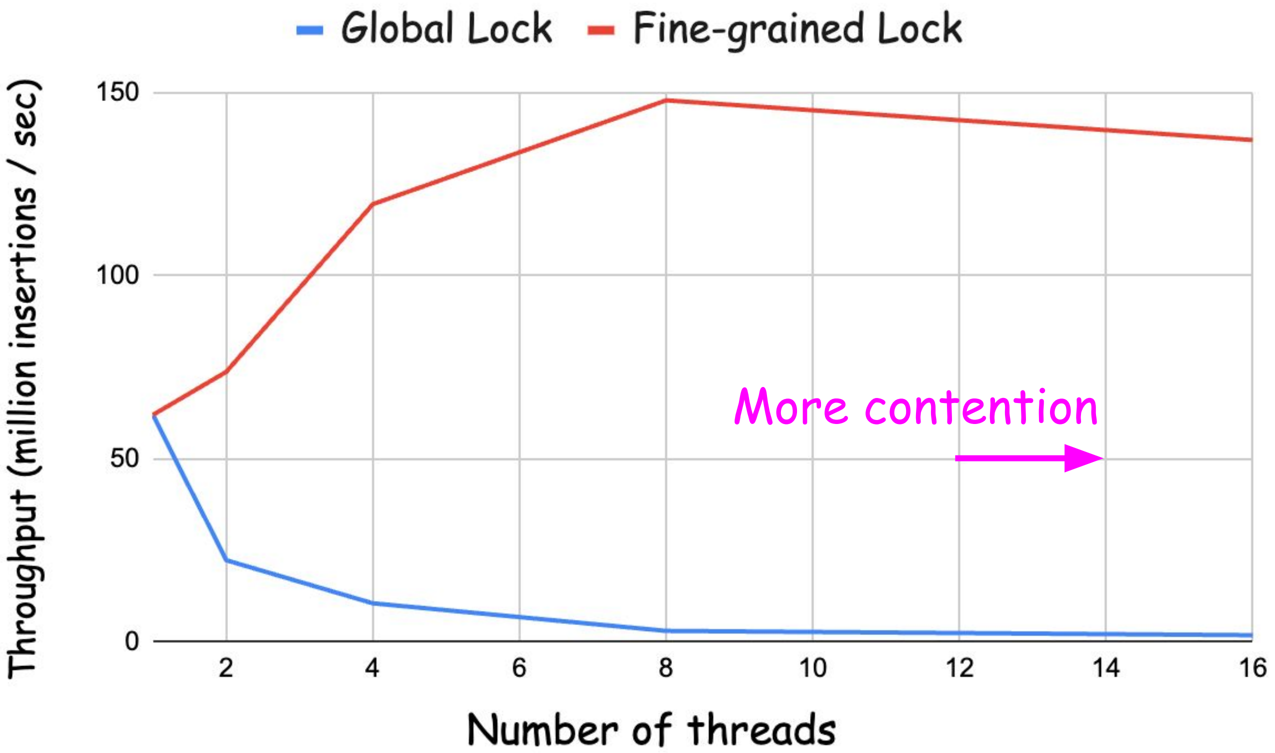

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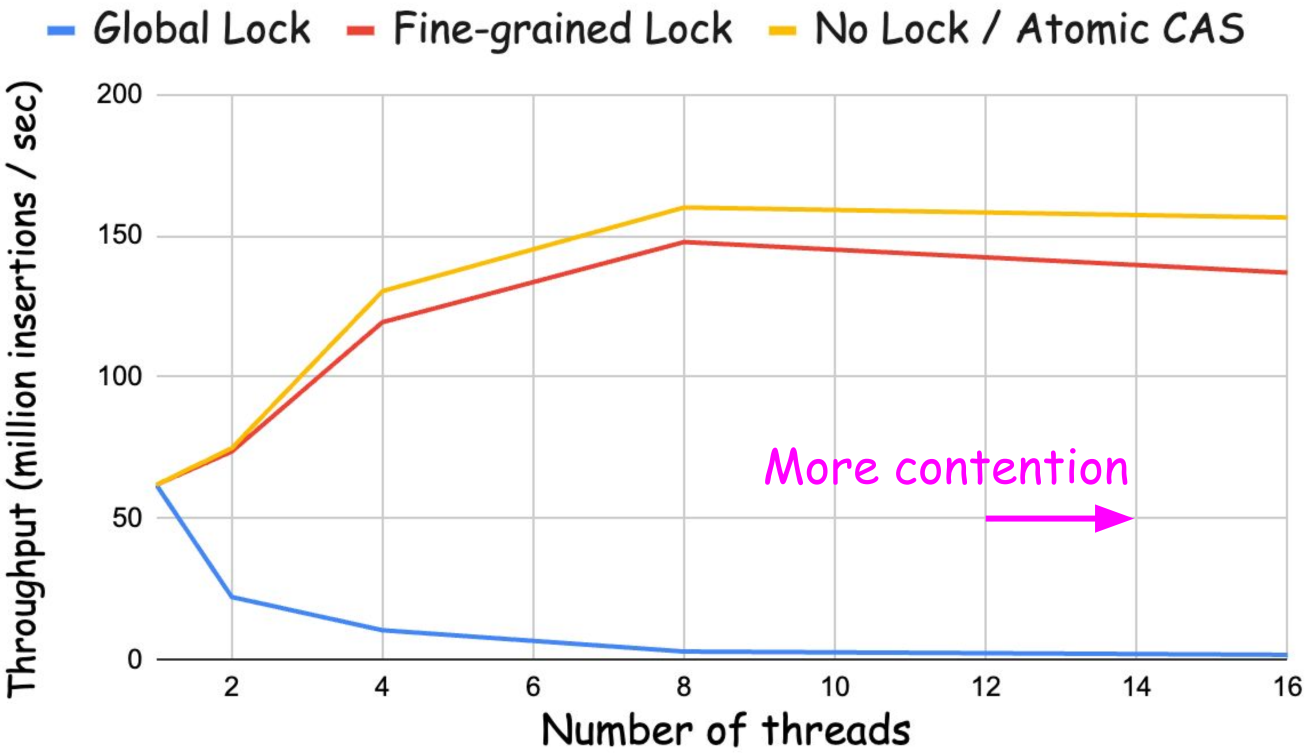
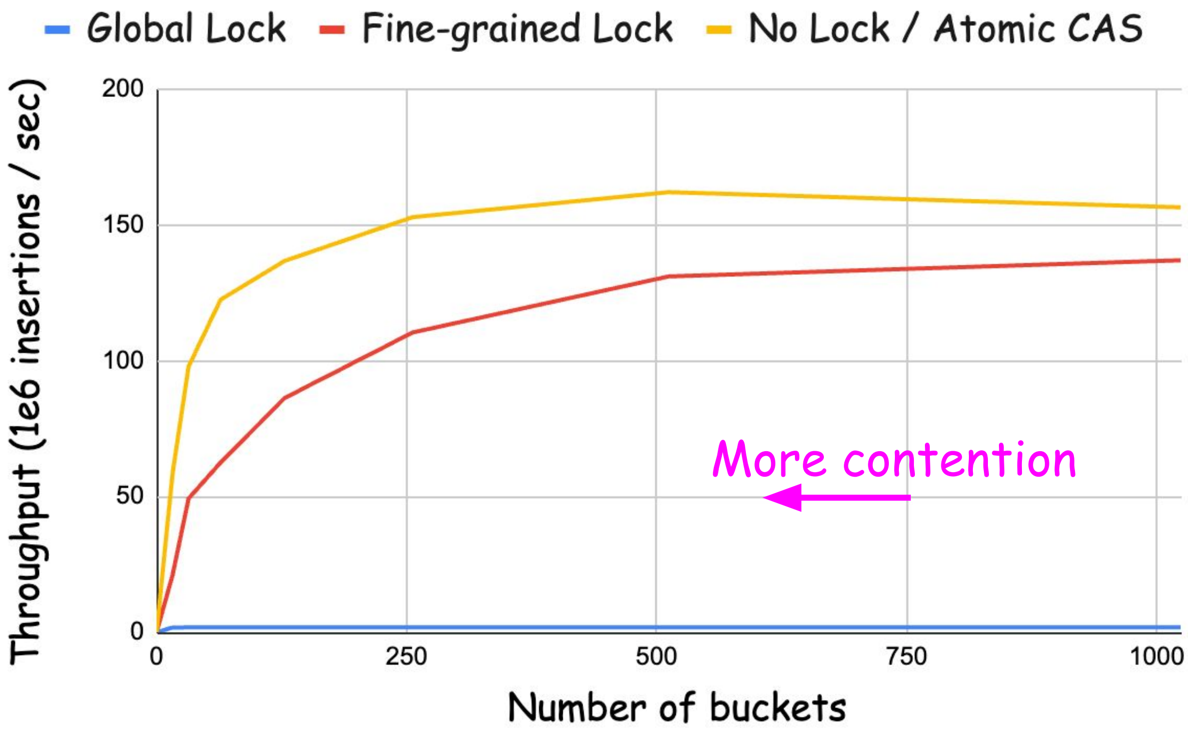


Understanding contention

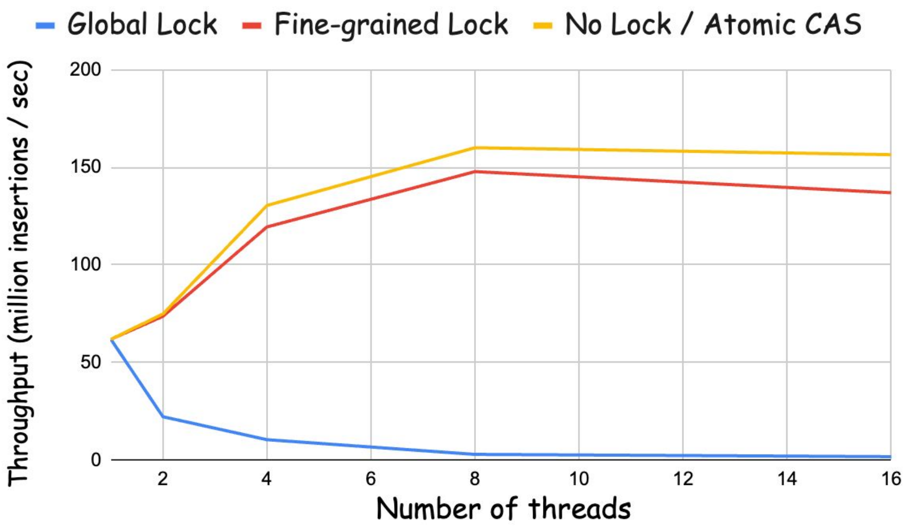
>> Random hash-table insertions, 16 (kernel) threads

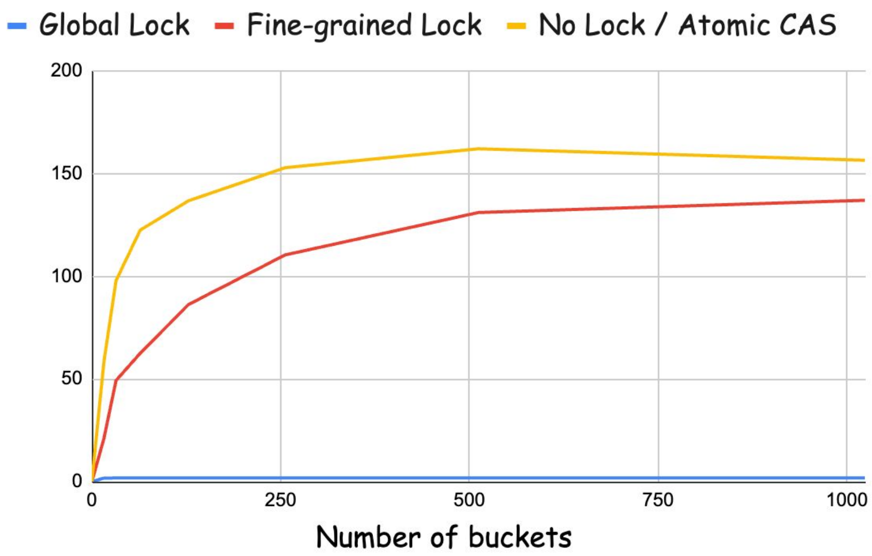


Understanding contention

>> Random hash-table insertions

- Which locking implementation would you choose?
- How many threads and how many buckets will you set?





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>> Hybrid kernel-/user-space locks: Can you avoid kernel intervention? when?

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Read more here: https://www.kernel.org/doc/html/v4.18/kernel-hacking/locking.htm

Deadlocks: Using locks incorrectly

>> What is a deadlock? **Unrecoverable error** where all members of a group of entities wait indefinitely on each other and cannot make progress, because each waits for another member of the group, including itself, to take action

Deadlocks: Using locks incorrectly

» **What causes a deadlock** (preconditions: "and")?

Deadlocks: Using locks incorrectly

» **What causes a deadlock** (preconditions: "and")?

1) Mutual Exclusion: Exclusive access on a shared resource
2) No preemption: Once the shared resource is obtained by a thread, it cannot be taken away involuntarily
3) Hold and Wait: A thread holding a shared resource is also waiting for additional resources, held by other threads
4) Circular Wait: There exists a set of waiting threads, $T = \{T_1, T_2, ..., T_n\}$, such that T_1 is waiting for a resource held by T_2, T_2 is waiting for a resource held by T_3, ..., and T_n is waiting for a resource held by T_1

Deadlock prevention: Proactive

» **How to prevent deadlocks** (proactively)? Remove one of the four AND preconditions

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» **How to prevent deadlocks** (proactively)? Remove one of the four AND preconditions

1) <u>No Mutual Exclusion:</u> No exclusive access on a shared resource
2) <u>Enable preemption:</u> No thread can hold the shared resource for more than a given time frame while others are trying to obtain it
3) <u>Avoid hold and wait:</u> No thread can hold the shared resource while requesting another, and must, instead, try to obtain all the necessary resources at once, at the beginning
4) <u>Avoid circular waiting:</u> Impose a hierarchical ordering on shared resource acquisition

Deadlock prevention: Proactive

» **How to prevent deadlocks** (proactively)? Remove one of the four AND preconditions

1) No Mutual Exclusion: No exclusive access on a shared resource...
2) Enable preemption: **Add timeout on the acquire operation, and raise an error if it expires while attempting to get the lock**
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3) Avoid hold and wait: No thread can hold the shared resource while requesting another, and must, instead, try to obtain all the necessary resources at once, at the beginning
4) Avoid circular waiting: **Developers follow this in practice by acquiring locks in a well-documented hierarchical order**

The dining philosophers problem

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> Typical CS problem — Everything we don't want, could happen

- Deadlock (i.e., no one can proceed): Could happen… How?
- Livelock (i.e., no real progress / no liveness): Could happen… How?
- Starvation (i.e., some no real progress): Could happen… How?

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    - Each philosopher needs two chopsticks to eat
    - Each philosopher can take either their left or their right chopstick
    - They cannot pick both chopsticks at once

> Typical CS problem — **Designing a correct solution**

The dining philosophers problem

- **Problem description:** N philosophers sitting around a circular table
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  - Avoid starvation: How?

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  - Avoid deadlocks: **How?** Break circular wait [P_n will not get C_n, if C_1 is held]
  - Avoid livelocks: **How?** Use random / exponential backoff
  - Avoid starvation: **How?** Use a queue, or an aging / ticket mechanism