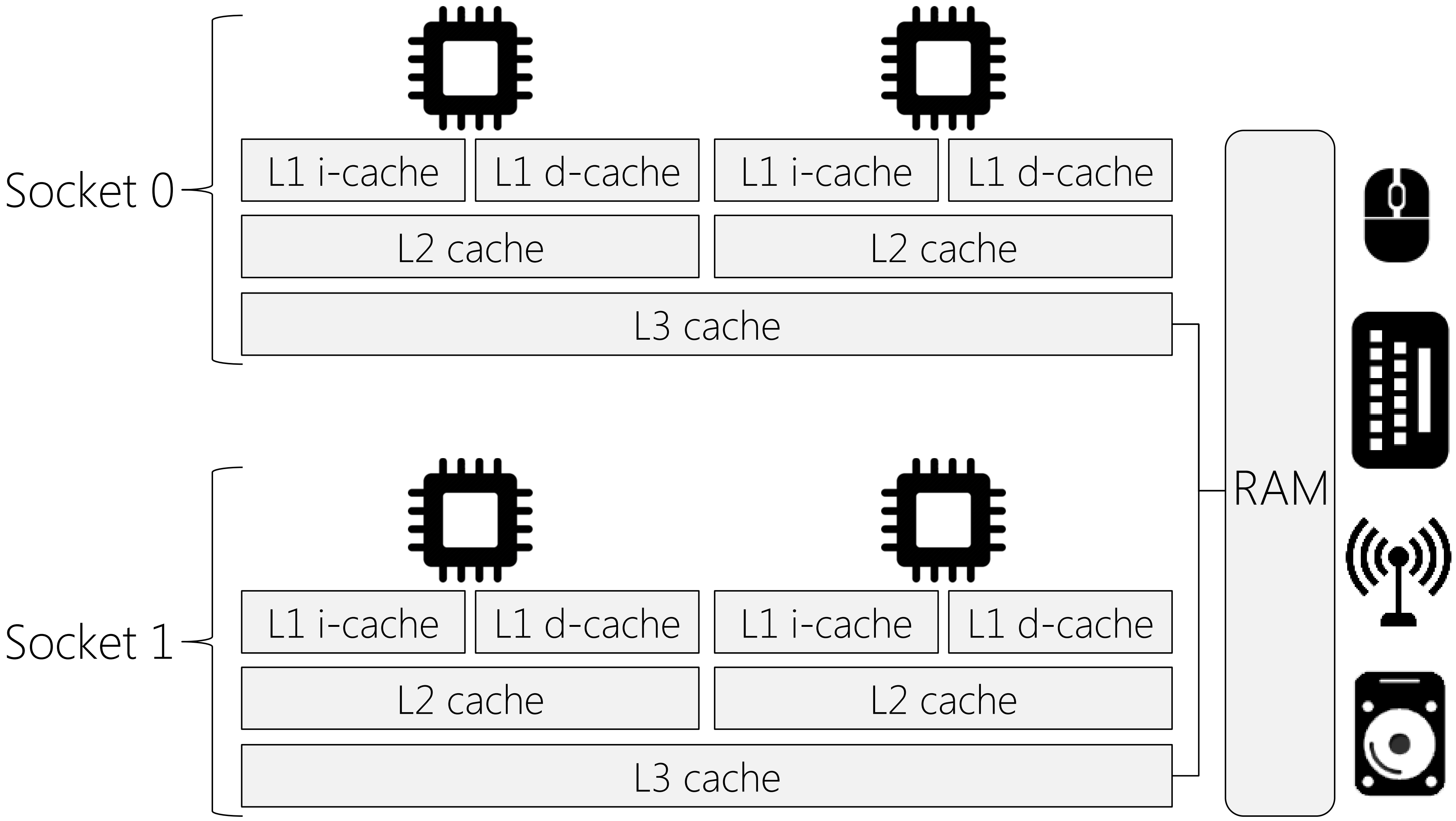
Scheduling: Case Studies

Scheduling Basics

- Goal of scheduling: Pick the “best” task to run on a CPU
  - Often a good idea to prioritize IO-bound tasks
    - If IO comes from user (e.g., keyboard, mouse), we want interactive programs to feel responsive
    - IO is typically slow, so start it early!

Inside a Computer



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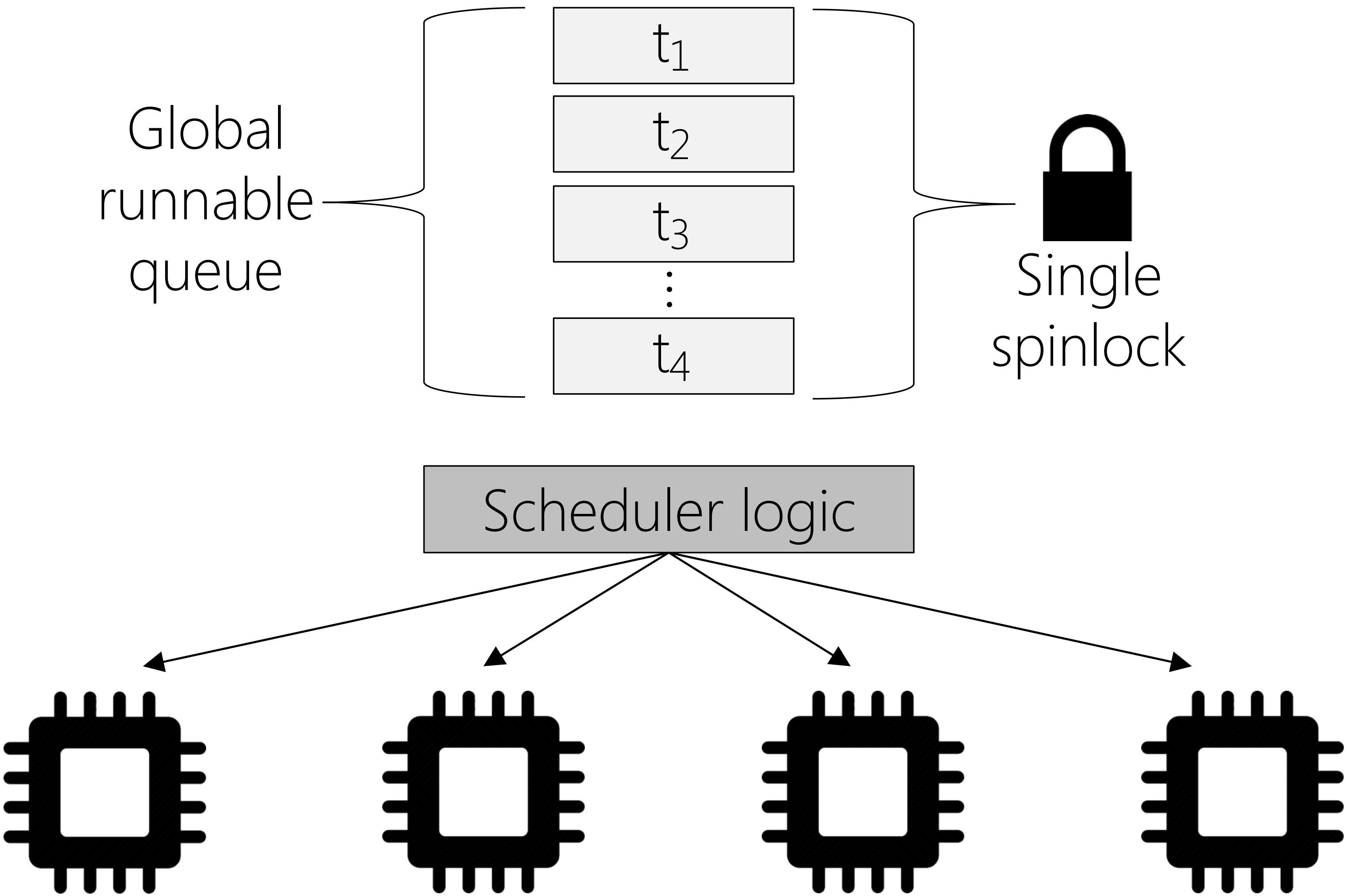
1 CPU cycle:	0.3 ns	
L1 cache access:	0.9 ns	
L2 cache access:	2.8 ns	
		1 OMag
L3 cache access:	12.9 ns	
		1 OMag
RAM access:	120 ns	
		3 OMags
SSD access:	50—150 μs	
		1—2 OMags
Disk access:	5—10 ms	
		1—2 OMags
Network RTT:	10—500 ms	
		1+ OMags
User input:	200 ms—seconds	

IO is slow, and other tasks need to run! (SSD access through User input)

Scheduling Basics

- Goal of scheduling: Pick the “best” task to run on a CPU
  - Often a good idea to prioritize IO-bound tasks
    - If IO comes from user (e.g., keyboard, mouse), we want interactive programs to feel responsive
    - IO is typically slow, so start it early!
- Fairness: All tasks should eventually get to run
- Scheduling speed: The scheduler is PURE OVERHEAD
  - Linux 2.4: O(n) scheduler
  - Linux 2.6.early: O(1) scheduler
  - Linux 2.6.23+: O(log n) CFS scheduler

Linux O(n) Scheduler



Each Task Has Three Priorities

- Static priorities (do not change over lifetime of task)
  - “Real-time” priority
    - Between 1 and 99 for “real-time” tasks, 0 for normal tasks
    - RT task runs to completion unless it issues a blocking IO, voluntarily yields, or is preempted by higher priority RT task
  - Niceness priority
    - Normally 0; set by “nice” command to [-20, 19]
- Dynamic priority
  - Scheduler divides time into epochs
  - At start of epoch, each task is assigned a positive counter value (“time slice”)
    - Unit is “scheduler ticks” or “jiffies”
    - #define HZ 1000 //Rate that the timer interrupt fires
  - Task’s time slice: remaining CPU time that task can use during the current epoch (measured in 1/HZ long quanta)
  - Timer interrupt decrements counter for currently executing task

```
void do_timer(){
  jiffies++;
  update_process_times();
}

void update_process_times(){
  struct task_struct *p = current;
  p->counter--;
  //Other bookkeeping involving
  //time statistics for this task
  //and the cpu the task is
  //running on.
}
```

Linux O(n) Scheduler

```
struct task_struct{
  unsigned long rt_priority;  //For “real-time” tasks
  int static_prio;            //The task’s nice value
  int counter;                //The task’s remaining
                              //time slice, i.e., the
                              //task’s dynamic priority
  ...
}
```

```
void schedule(){
    struct task_struct *next, *p;
    struct list_head *tmp;
    int this_cpu = ..., c;

    spin_lock_irq(&runqueue_lock); //Grabs global lock.
    next = idle_task(this_cpu);
    c = -1000; //Best goodness seen so far.
    list_for_each(tmp, &runqueue_head){
        p = list_entry(tmp, struct task_struct, run_list);
        if (can_schedule(p, this_cpu)) {
            int weight = goodness(p);
            if(weight > c){
                c = weight;
                next = p;
            }
        }
    }
    spin_unlock_irq(&runqueue_lock);
    switch_to(next, ...);
}
```

```
struct task_struct{
  volatile long state;//-1 unrunnable,
                      // 0 runnable,
                      // >0 stopped
  int exit_code;
  struct mm_struct *mm;
  unsigned long cpus_allowed;
       //bitmask representing which
       //cpus the task can run on
  ...
};
```

Calculating Goodness

```
int goodness(struct task_struct *p){
    if(p->policy == SCHED_NORMAL){
        //Normal task
        if(p->counter == 0){
            //Task has used all of its
            //time for this epoch!
            return 0;
        }
        return p->counter + 20 – p->nice;
    }else{
        //“Real-time” task
        return 1000 + p->rt_priority;
               //Will always be
               //greater than
               //priority of a
               //normal task
    }
}
```

The dynamic priority (i.e., time slice)

Linux “nice” command or nice() sys call: Increase or decrease static priority by [-20, +19]

```
void schedule(){
   struct task_struct *next, *p;
   struct list_head *tmp;
   int this_cpu = ..., c;

   spin_lock_irq(&runqueue_lock);
   next = idle_task(this_cpu);
   c = -1000; //Best goodness seen so far.
   list_for_each(tmp, &runqueue_head){
       p = list_entry(tmp, struct task_struct, run_list);
       if (can_schedule(p, this_cpu)) {
           int weight = goodness(p);
           if(weight > c){
               c = weight;
               next = p;
           }
       }
   }
   spin_unlock_irq(&runqueue_lock);
   switch_to(next);
}
```

Pick highest priority "real time" task; if no such task, pick the normal task with the largest sum of static priority and remaining time slice

```
void schedule(){
   struct task_struct *next, *p;
   struct list_head *tmp;
   int this_cpu = ..., c;

   spin_lock_irq(&runqueue_lock);
   next = idle_task(this_cpu);
   c = -1000; //Best goodness seen so far.
   list_for_each(tmp, &runqueue_head){
       p = list_entry(tmp, struct task_struct, run_list);
       if (can_schedule(p, this_cpu)) {
           int weight = goodness(p);
           if(weight > c){
               c = weight;
               next = p;
           }
       }
   }
   spin_unlock_irq(&runqueue_lock);
   switch_to(next);
}
```

```
repeat_schedule:
```

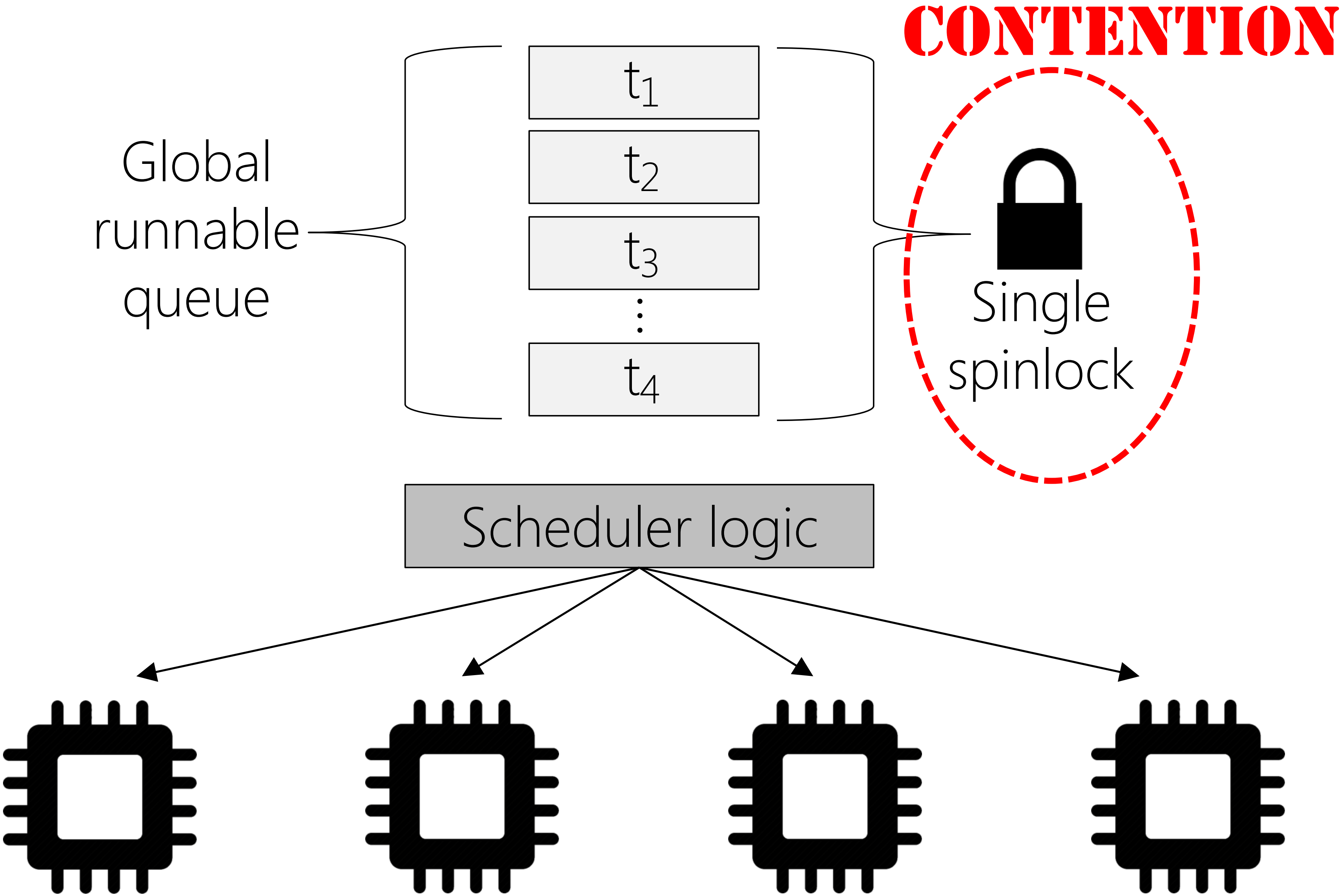
Boost priority of interactive tasks which sleep often!

```
if(!c){//c==0, no good tasks!
  struct task_struct *p;
  spin_unlock_irq(&runqueue_lock);
  read_lock(&tasklist_lock);
  for_each_task(p){
    p->counter = (p->counter >> 1) +
                NICE_TO_TICKS(p->nice);
  }//Counters for next epoch now set
  read_unlock(&tasklist_lock);
  spin_lock_irq(&runqueue_lock);
  goto repeat_schedule;
}
```

Summary: Linux O(n) Scheduler

- "Real-time" tasks have high, unchanging static priority
- Regular tasks have low static priority, and low, dynamically changing priority
  - Dynamic priority (time slice) set at epoch start
  - Time slice decremented as task uses CPU
- When scheduler must pick a task:
  - Search runnable queue for task with best goodness — O(n)
  - If all runnable tasks have goodness == 0, recalculate all time slices, then search runnable queue again — O(n)
  - Once a task has a counter of 0, it cannot run again until the new epoch arrives!

Another problem . . .



Why Was The O(n) Scheduler Tolerated?

DRAKE IS ANGRY

The O(n) Scheduler Isn't That Bad!

DRAKE IS HAPPY

PREMATURE OPTIMIZATION IS THE ROOT OF ALL EVIL.

Simple is better unless proven otherwise.

Thy shall profile before thy shall optimize.

Linux O(1) Scheduler

- Goal 1: Get sublinear scheduling overhead
- Goal 2: Remove contention on a single, global lock

```
struct task_struct{
  unsigned long rt_priority;  //For “real-time” tasks
  int static_prio;            //The task’s nice value
  unsigned int time_slice;    //CPU time left in epoch
  int prio;                   //The task’s “goodness”
  unsigned long sleep_avg;    //Estimate of how long
                              //task spends blocked on
                              //IO versus executing on
                              //CPU; goes up when task
                              //sleeps, goes down when
                              //task runs on CPU
  ...
}
```

Linux O(1) Scheduler

- Goal 1: Get sublinear scheduling overhead
- Goal 2: Remove contention on a single, global lock

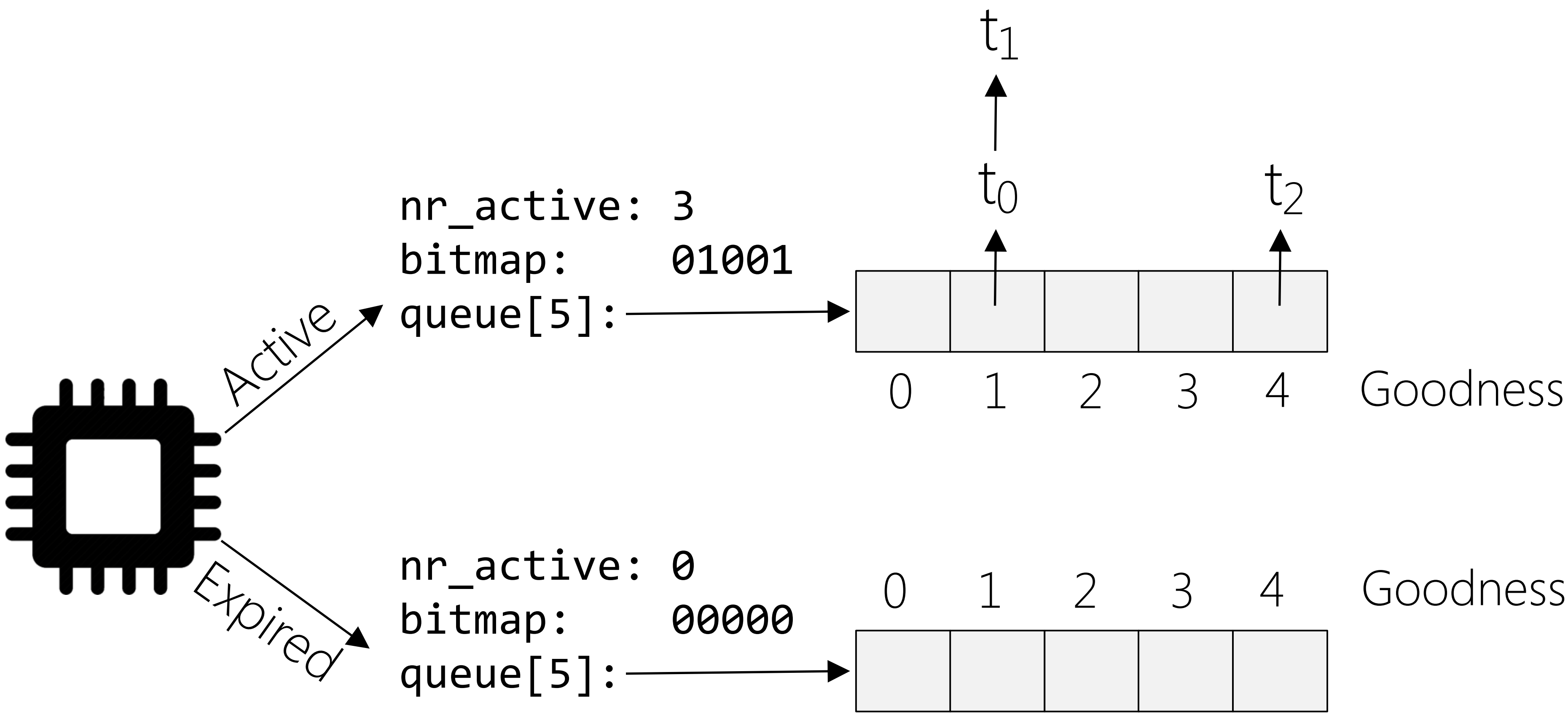
```
struct runqueue{
    spinlock_t lock;
    struct task_struct *curr;
    prio_array_t *active;
    prio_array_t *expired;
    ...
}
```

Per-cpu

```
struct prio_array{
    unsigned int nr_active;
    struct list_head queue[MAX_PRIO];
    unsigned long bitmap[BITMAP_SIZE];
};
```

Think of queue as being indexed by "goodness" schedule()

- Find the first non-empty queue
- Run the first task in the list



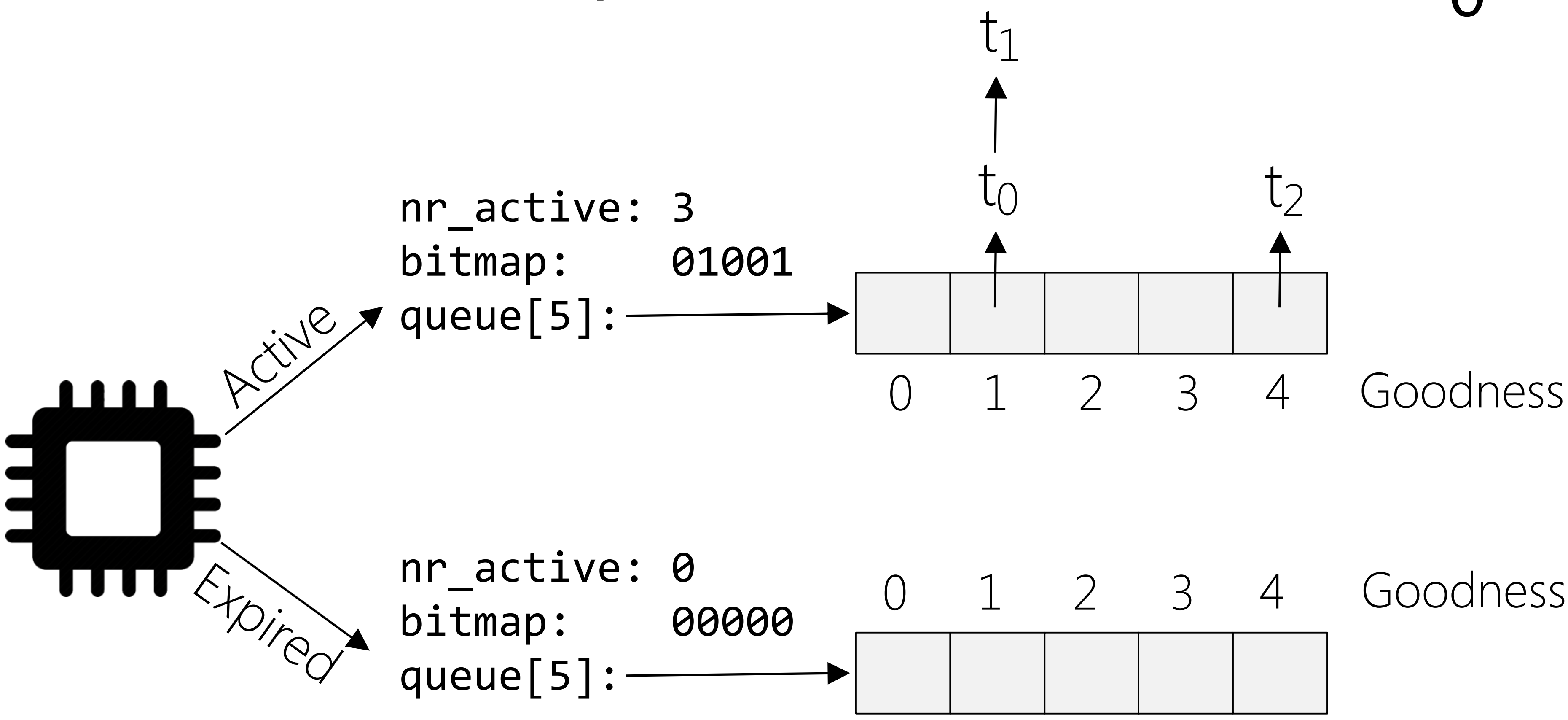
```
void scheduler_tick(){ //Called by the timer interrupt.
    runqueue_t *rq = this_rq();
    task_t *p = current;

    spin_lock(&rq->lock);
    if(!--p->time_slice){
       dequeue_task(p, rq->active);
       p->prio = effective_prio(p);
       p->time_slice = task_timeslice(p);
       if(!TASK_INTERACTIVE(p) ||
           EXPIRED_STARVING(rq)){
           enqueue_task(p, rq->expired);
       }else{ //Add to end of queue.
           enqueue_task(p, rq->active);
       }
    }else{ //p->time_slice > 0
       if(TASK_INTERACTIVE(p)){
           //Probably won't need the CPU
           //for a while.
           dequeue_task(p, rq->active);
           enqueue_task(p, rq->active); //Adds to end.
       }
    }
    spin_unlock(&rq->lock); //Later, interrupt handler calls schedule().
}
```

```
//Calculate "goodness".
int effective_prio(task_t *p){
  if(rt_task(p))
     return p->prio;
  bonus = CURRENT_BONUS(p);
         //Bonus higher if
         //p->sleep_avg is big
  return p->static_prio –
         bonus;
         //static_prio is p's
         //nice value
}
```

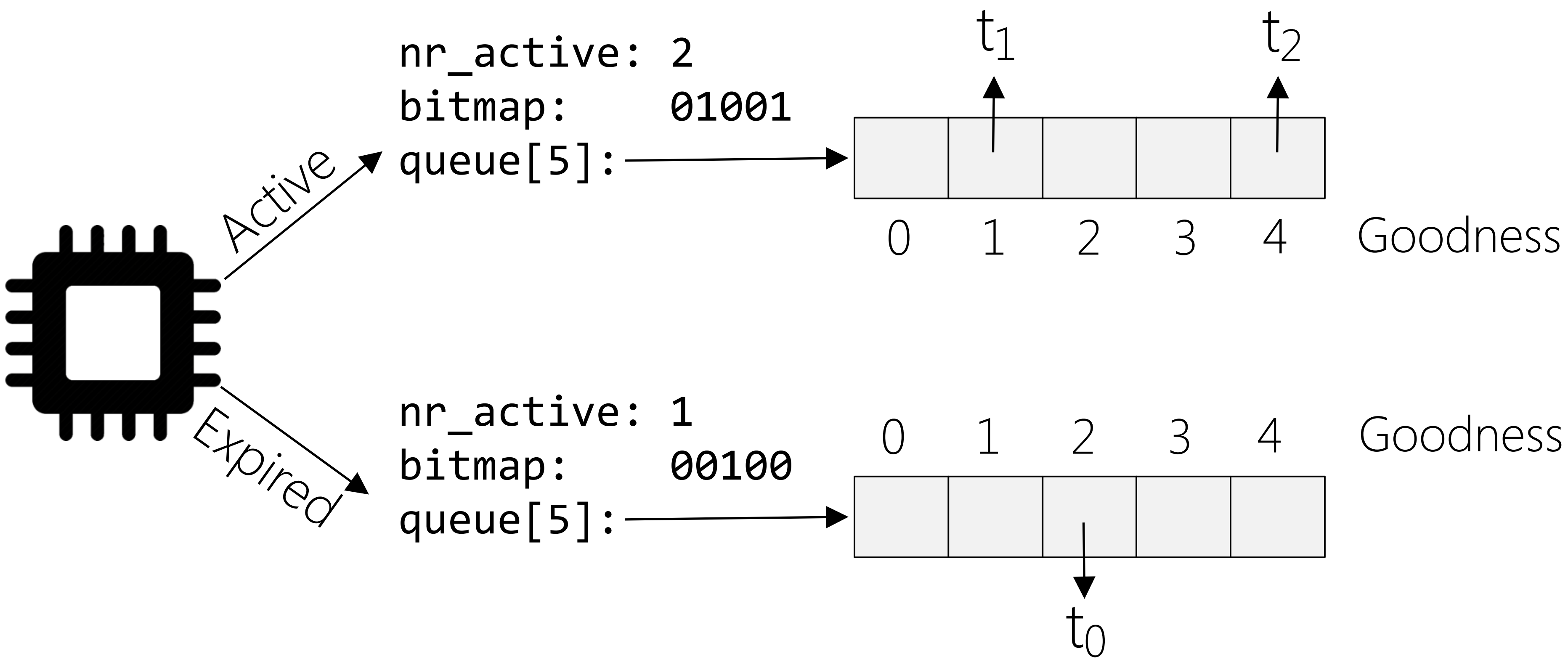
```
//Time slices calculated
//incrementally, unlike
//O(n) scheduler! High
//priority tasks get
//longer time slices.
```

THIS IS NOT A PORSCHE

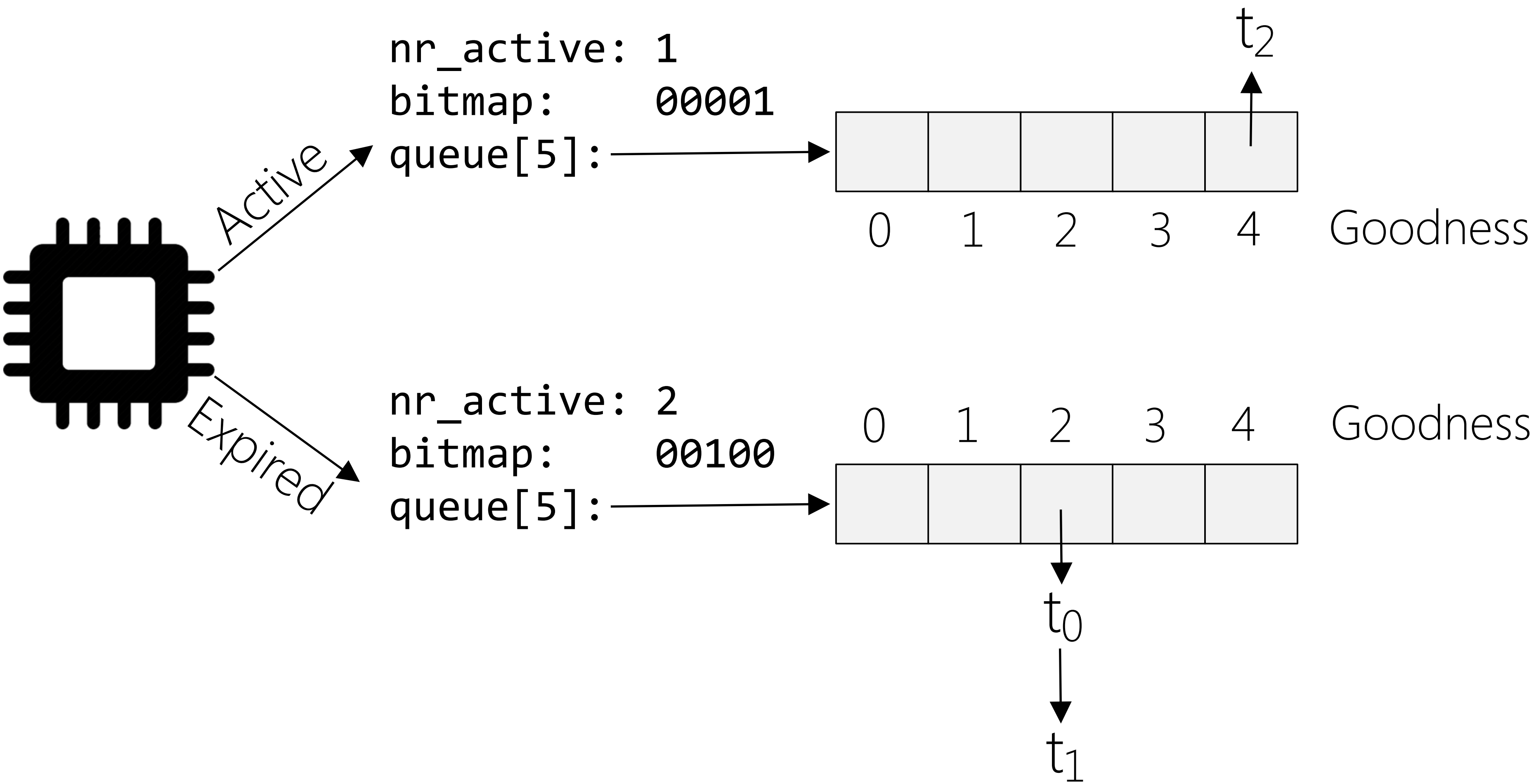
Timer interrupt fires, scheduler runs t_0



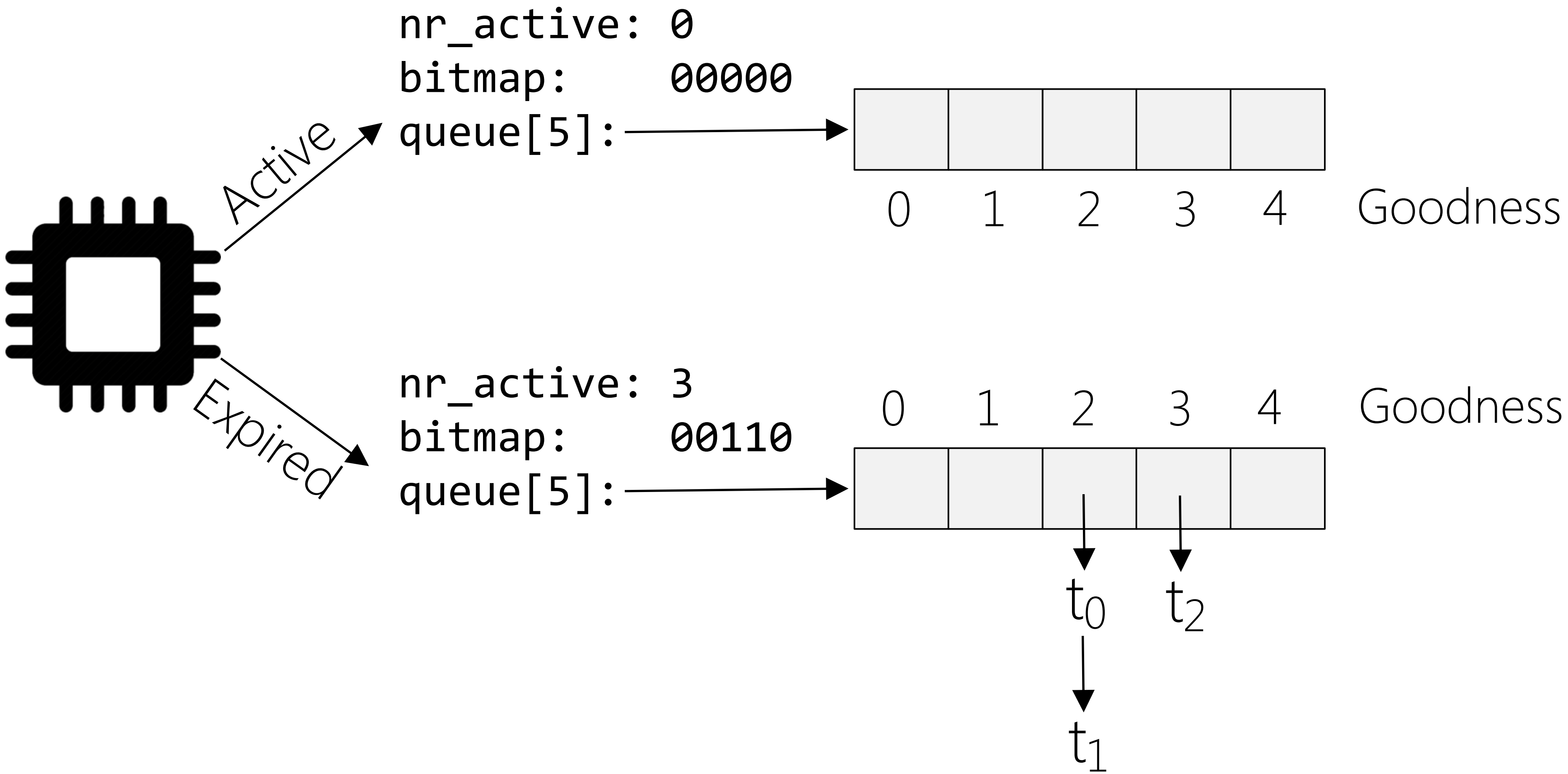
Timer interrupt fires, scheduler moves t_0 to expired list, runs t_1



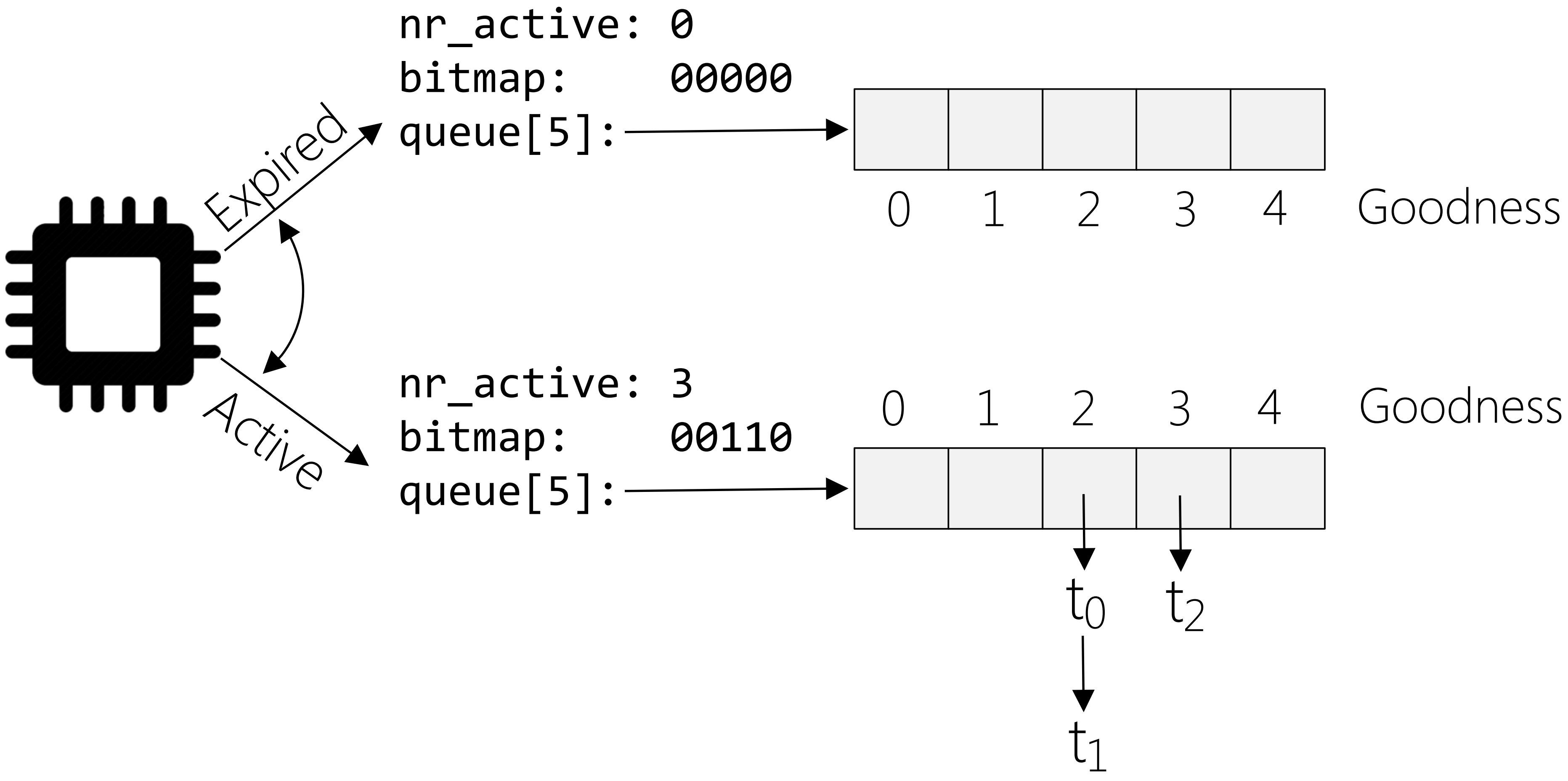
Timer interrupt fires, scheduler moves t_1 to expired list, runs t_2



Later, scheduler moves t_2 to the expired list



Scheduler notices that nr_active is 0, and swaps the “active” and “expired” pointers: O(1) running time!



Summary: Linux O(1) Scheduler

- Per-processor scheduling data structures (eliminate global lock!)
  - Active array of queues (1 queue per priority level)
  - Expired array of queues (1 queue per priority level)
  - Task priority: ("real-time" priority) or (nice value + bonus)
- Scheduler picks first task from highest priority non-empty active queue
  - Finding that queue is O(1): find first 1 bit via hardware instruction
- Timer interrupt decrements time slice for current task
  - If time slice is 0, move task to queue in expired array . . .
  - . . . unless task is interactive: maybe keep it active!
  - Eventually force even high priority interactive tasks into expired array (avoids starvation)
- When active array queues are empty, flip array pointers: O(1)

Multi-level Feedback Queuing

- Goal: Use static priorities and history to find the right scheduling strategy for a task
  - Scheduler uses task history to guess whether task is interactive (IO-bound, should get CPU when runnable) or CPU-bound
  - Static priorities are hints that programmers give to scheduler
- Rule 1: If Priority(A) > Priority(B), schedule A
- Rule 2: A task that sleeps a lot is likely to be interactive (and should receive a high priority)
- Rule 3: A task that uses its full time slice is probably demoted (but see Rule 2)
- Rule 4: No starvation (every task eventually runs!)

Linux's "Completely Fair Scheduler" (CFS)

- The O(1) scheduler is fast, but hackish
  - Heuristics (e.g., TASK_INTERACTIVE(p) and EXPIRED_STARVING(rq)) are complex, seem gross, have corner cases that are unfair
  - CFS invented to provide a more "elegant" solution

Linux's "Completely Fair Scheduler" (CFS)

- For now, make these simplifying assumptions:
  - There is only one CPU
  - All tasks have the same priority
  - There are always T tasks ready to run at any moment
- Basic idea in CFS: each task gets 1/T of the CPU's resources
  - Ideal CPU: Runs each task simultaneously, but at 1/T the CPU's clock speed
  - Real CPU: Can only run a single task at once!
  - CFS tracks how long each task has actually run; during a scheduling decision (e.g., timer interrupt), picks the task with lowest runtime so far

Red-black binary tree

- Self-balancing: Insertions and deletions ensure that longest tree path is at most twice the length of any other path
- Guaranteed logarithmic time: Insertions, deletions, and searches all run in O(log N) time

CFS scheduler

- Associate each task with its elapsed runtime (nanosecond granularity)
- Keep all runnable tasks in a red-black tree
- Next task to run is just the left-most task in tree!

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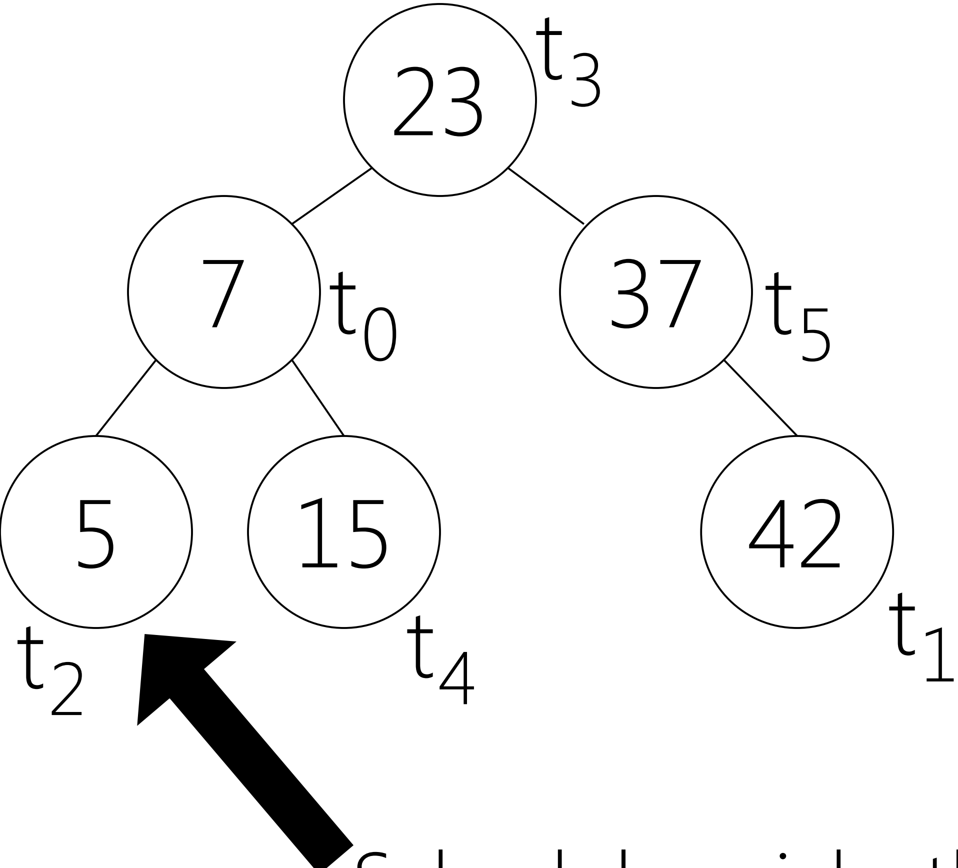
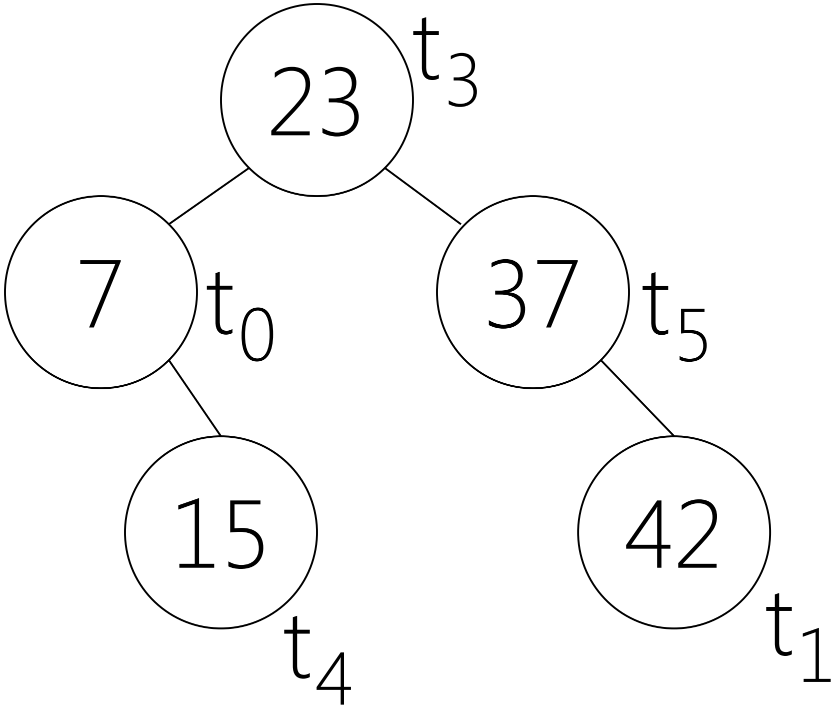


Scheduler picks this task to run, removes it from tree



Timer interrupt fires, scheduler runs

- Now, t_2 no longer has the smallest elapsed runtime
- So, scheduler reinserts t_2 into the tree and runs t_0!

Classic CFS Example

- Suppose there are two tasks:
  - Video rendering application (CPU-intensive, long running, non-interactive)
  - Word processor (interactive, only uses CPU for bursts)
- Both tasks start with an elapsed runtime of 0
  - Video rendering task quickly accumulates runtime . . .
  - . . . but word processor's runtime stays low (task is mainly blocked on IO)
- So, whenever word processor receives keyboard/mouse input and wakes up, it will be the left-most task, and immediately get scheduled

Task Priorities in CFS

```
/*
 * Nice levels are multiplicative, with a gentle 10% change for every
 * nice level changed. I.e. when a CPU-bound task goes from nice 0 to
 * nice 1, it will get ~10% less CPU time than another CPU-bound task
 * that remained on nice 0.
 *
 * The "10% effect" is relative and cumulative: from _any_ nice level,
 * if you go up 1 level, it's -10% CPU usage, if you go down 1 level
 * it's +10% CPU usage. (to achieve that we use a multiplier of 1.25.
 * If a task goes up by ~10% and another task goes down by ~10% then
 * the relative distance between them is ~25%.)
 */
static const int prio_to_weight[40] = {
 /* -20 */     88761,     71755,     56483,     46273,     36291,
 /* -15 */     29154,     23254,     18705,     14949,     11916,
 /* -10 */      9548,      7620,      6100,      4904,      3906,
 /*  -5 */      3121,      2501,      1991,      1586,      1277,
 /*   0 */      1024,       820,       655,       526,       423,
 /*   5 */       335,       272,       215,       172,       137,
 /*  10 */       110,        87,        70,        56,        45,
 /*  15 */        36,        29,        23,        18,        15,
};
```

Task Priorities in CFS

- CFS incorporates static priorities by scaling task's elapsed runtime

```
delta_exec = now – curr->exec_start;
delta_exec_weighed = delta_exec *
            (NICE_0_LOAD / t->load.weight);
curr->vruntime += delta_exec_weighted;
```

- The end result is that:
  - [nice=0] Virtual execution time **equals** physical execution time
  - [nice<0] Virtual execution time **less than** physical execution time
  - [nice>0] Virtual execution time **greater than** physical execution time
- curr->vruntime is used as a task's key in the RB tree

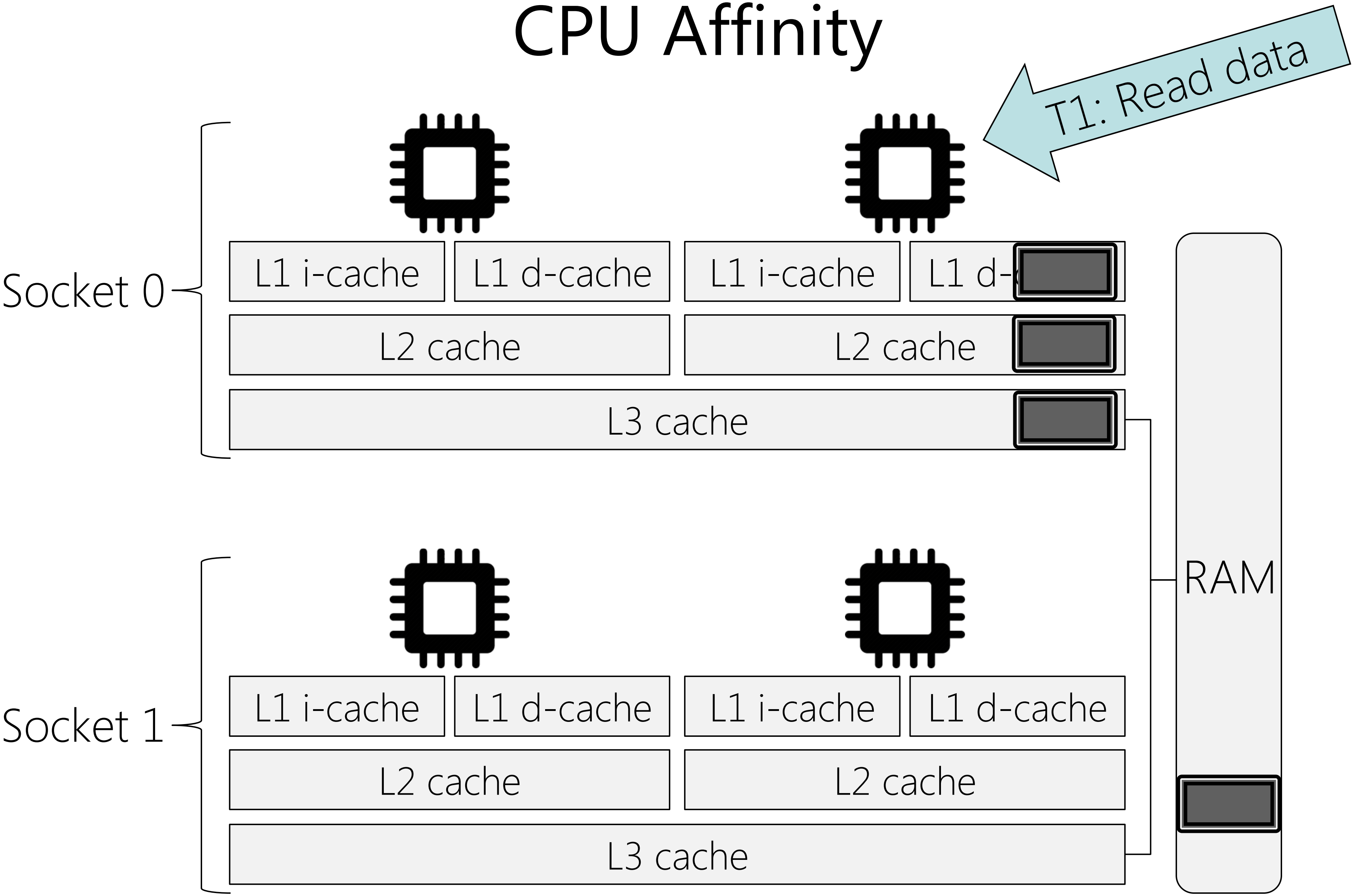
Summary: Linux CFS Scheduler

- Scheduler associates each task with elapsed runtime (not timeslice!)
  - Nanosecond-granularity tracking instead of jiffy granularity
  - Growth rate is modulated by task priority
- Scheduler maintains a per-core red-black tree
  - Tasks inserted using elapsed runtimes as keys
  - Left-most task is the task to run next!
  - Scheduling operations take O(log n) time
- Is CFS actually better than the O(1) scheduler? Hmmm . . .
  - Nanosecond-granularity elapsed runtimes seems better than jiffy-granularity timeslices . . .
  - . . . but O(1) seems faster than O(log n)?
  - vruntime values do seem fairer than timeslices/goodness/etc . . .
  - . . . but CFS has janky heuristics, just like the O(1) scheduler (Ex: "Usually run left-most task, unless we want to run the most recently preempted task to preserve cache locality")

CPU Affinity

```
struct task_struct{
    volatile long state;//-1 unrunnable,
                        // 0 runnable,
                        // >0 stopped
    int exit_code;
    struct mm_struct *mm;
    unsigned long cpus_allowed;
          //bitmask representing which
          //cpus the task can run on
    ...
};
```

CPU Affinity



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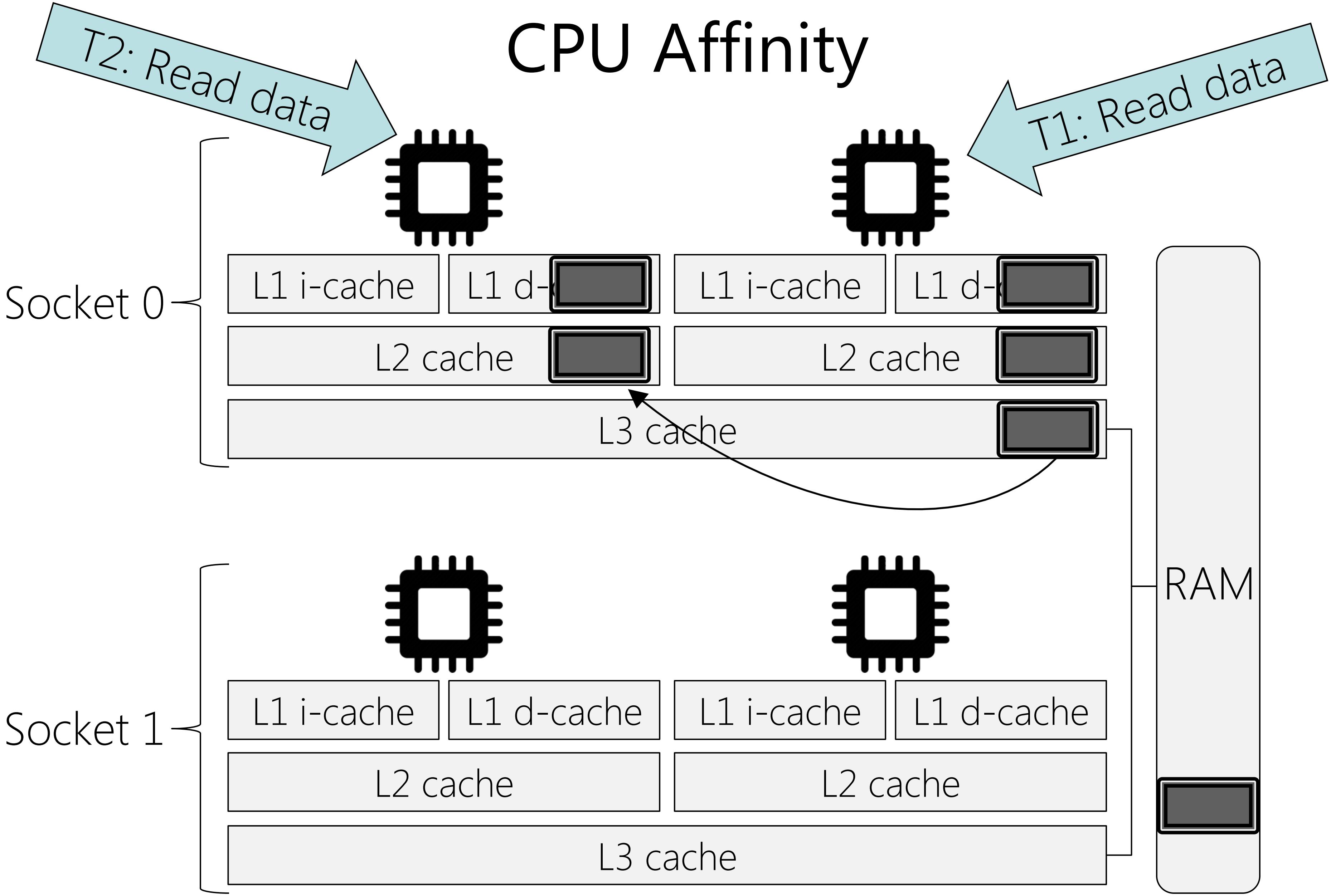

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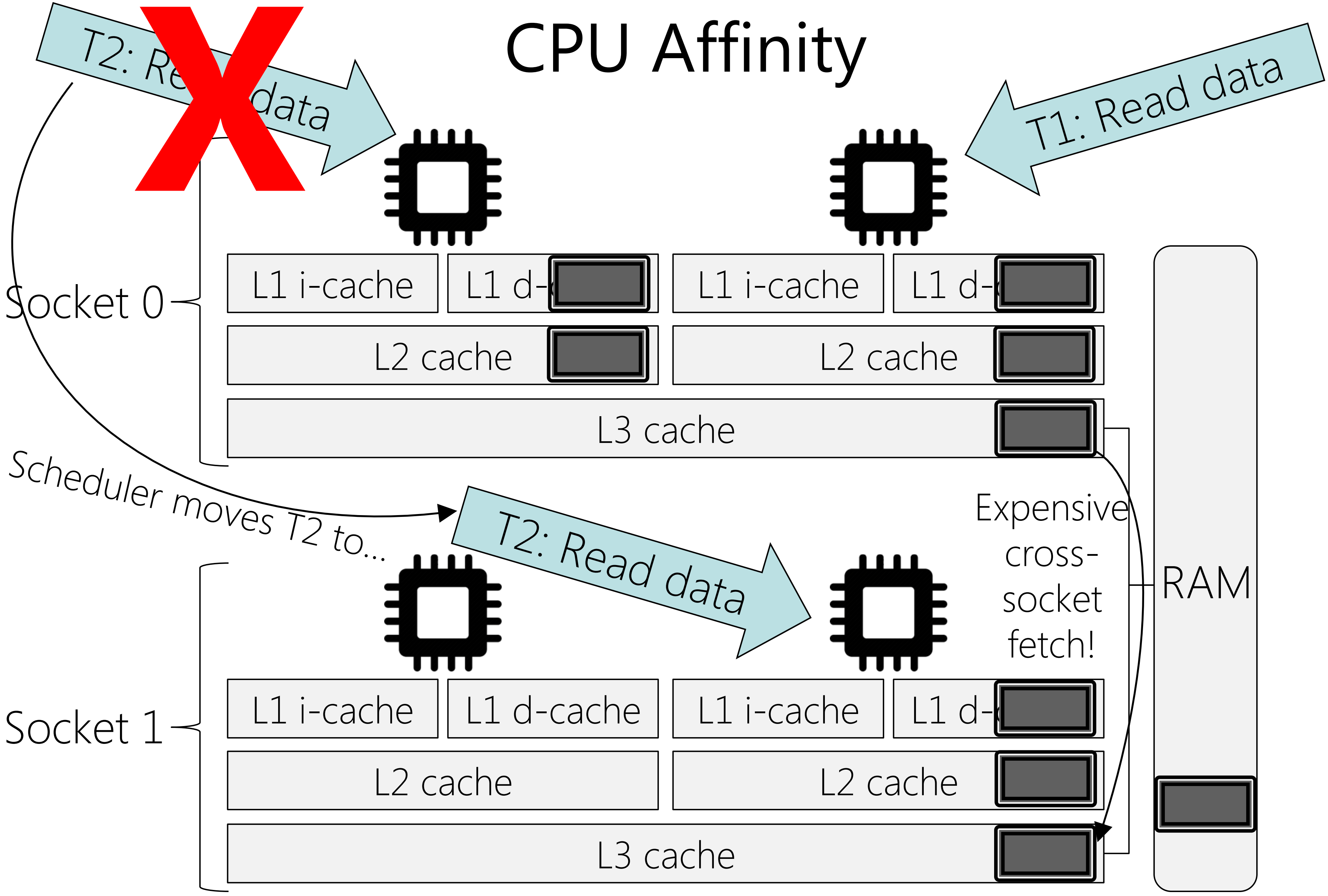

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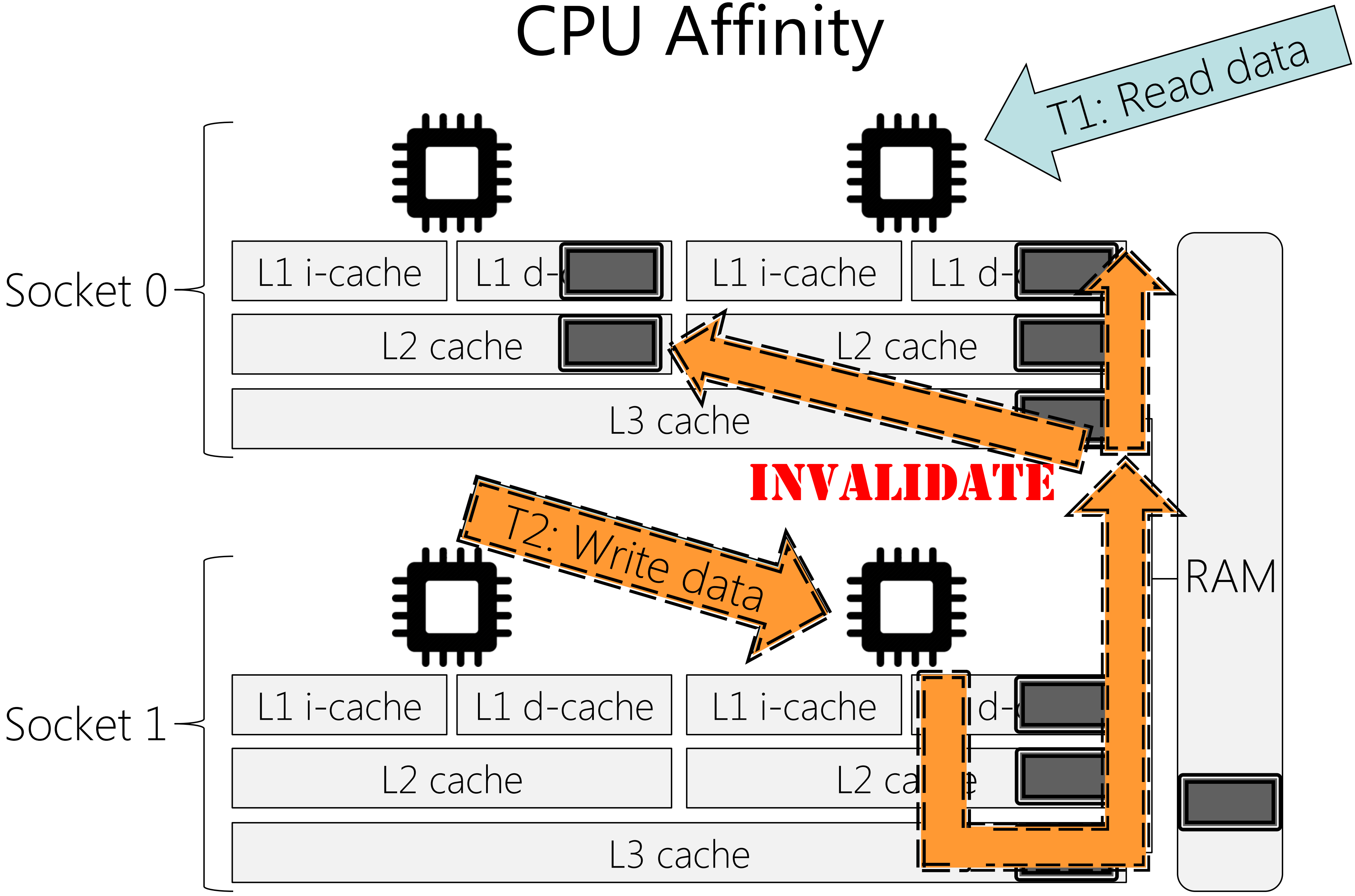

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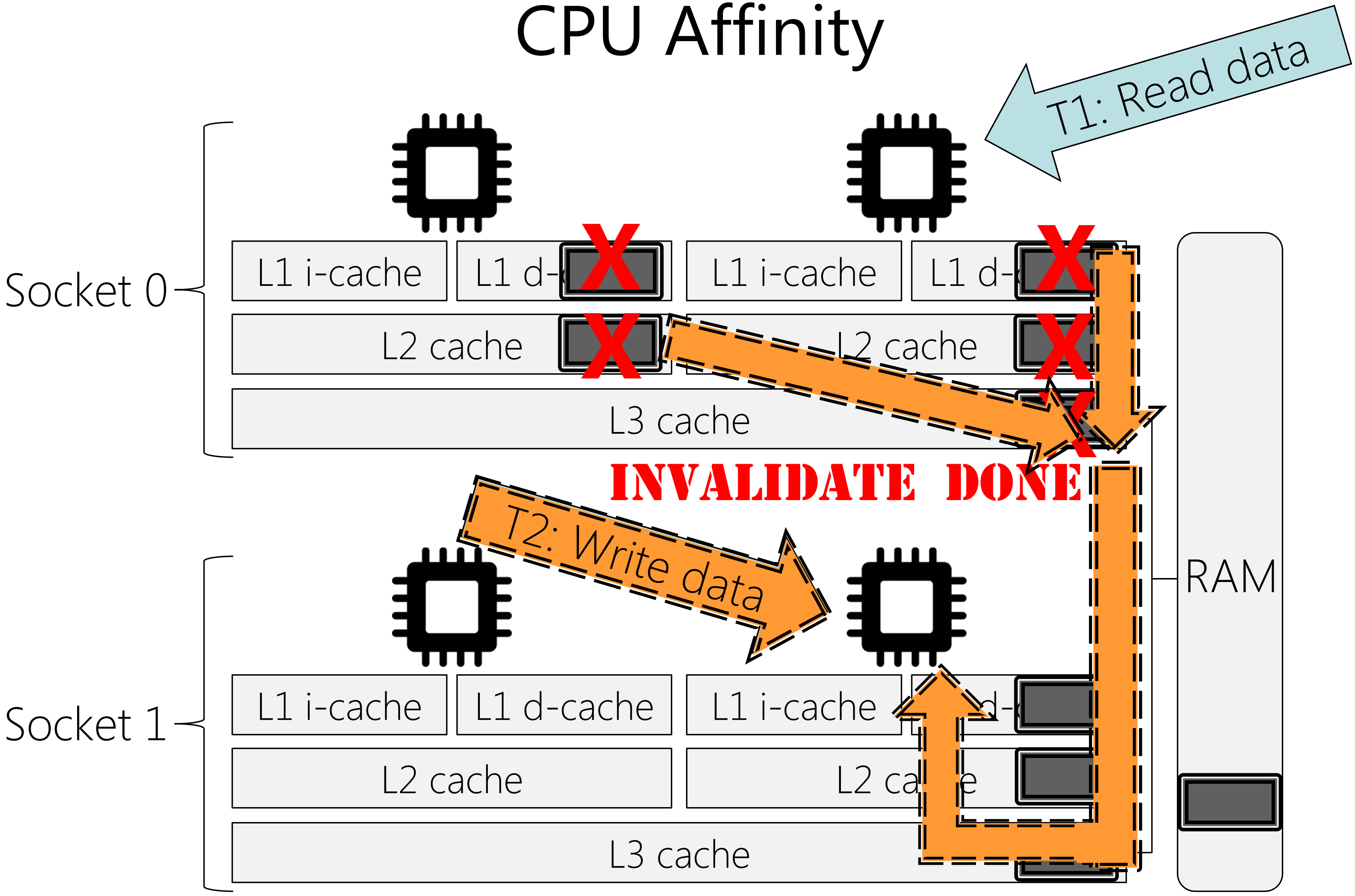

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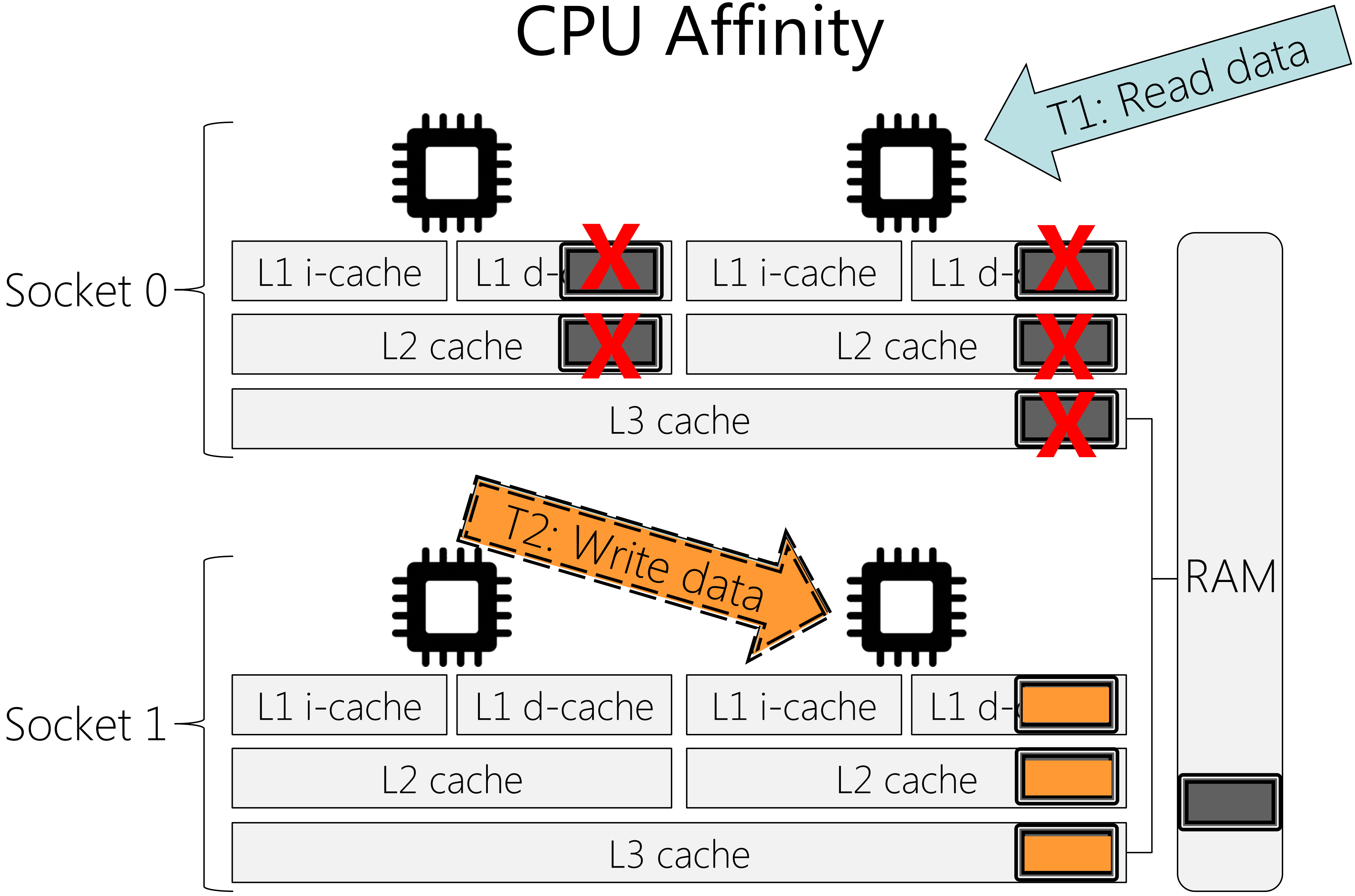

Your Machine is a Distributed System!

- Components are connected by a network
  - Some components talk directly (e.g., core/registers)
  - Others require multiple hops to communicate (e.g., core and L3 cache; two cores on different sockets)
  - More hops = more communication latency!
- OS scheduler tries to:
  - Avoid network latencies in the first place (e.g., using CPU affinity to reduce cache misses+invalidations)
  - Do something useful while waiting on unavoidable latencies (e.g., give high priority to IO-bound tasks, so that they can issue IOs, then sleep, allowing CPU-bound tasks to run while IOs complete)