cs5460/6460: Operating Systems

Lecture: Synchronization

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Starting other CPUs

Started from main()

```
1317 main(void)
1318 {
...
1336   startothers(); // start other processors
1337   kinit2(P2V(4*1024*1024), P2V(PHYSTOP));
1338   userinit(); // first user process
1339   mpmain();
1340 }
```

Starting other CPUs

- Copy start code in a good location
  - 0x7000
- Pass start parameters on the stack
- Allocate a new stack for each CPU
- Send a magic inter-processor interrupt (IPI) with the entry point (mpenter())

Start other CPUs

```
startothers(void)
{
  code = P2V(0x7000);
  memmove(code, _binary_entryother_start,
    (uint)_binary_entryother_size);

  for(c = cpus; c < cpus+ncpu; c++){
    if(c == cpus+cpunum()) // We’ve started already.
      continue;
...
    stack = kalloc();
    *(void**)(code−4) = stack + KSTACKSIZE;
    *(void**)(code−8) = mpenter;
    *(int**)(code−12) = (void *) V2P(entrypgdir);

    lapicstartap(c−>apicid, V2P(code));
```

Start other CPUs

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    lapicstartap(c->apicid, V2P(code));
```

- Allocate a new kernel stack for each CPU
- What will be running on this stack?

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Start other CPUs

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```

- Allocate a new kernel stack for each CPU
- What will be running on this stack?
- Scheduler

Start other CPUs

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- What is done here?

Start other CPUs

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  memmove(code, _binary_entryother_start,
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  for(c = cpus; c < cpus+ncpu; c++){
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    *(void**)(code-4) = stack + KSTACKSIZE;
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    *(int**)(code-12) = (void *) V2P(entrypgdir);

    lapicstartap(c->apicid, V2P(code));
```

- What is done here?
- Kernel stack
- Address of mpenter()
- Physical address of entrypgdir

Start other CPUs

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startothers(void)
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    *(void**)(code-8) = mpenter;
    *(int**)(code-12) = (void *) V2P(entrypgdir);

    lapicstartap(c->apicid, V2P(code));
```

- Send “magic” interrupt
- Wake up other CPUs

entryother.S

- Disable interrupts
- Init segments with 0

```
.code16
.globl start
start:
  cli

  xorw %ax,%ax
  movw %ax,%ds
  movw %ax,%es
  movw %ax,%ss

```

entryother.S

```
  lgdt gdtdesc
  movl %cr0, %eax
  orl $CR0_PE, %eax
  movl %eax, %cr0
  ljmpl $(SEG_KCODE<<3), $(start32)

.code32
start32:
  movw $(SEG_KDATA<<3), %ax
  movw %ax, %ds
  movw %ax, %es
  movw %ax, %ss
  movw $0, %ax
  movw %ax, %fs
  movw %ax, %gs
```

- Load GDT
- Switch to 32bit mode
- Long jump to start32
- Load segments

```
# Turn on page size extension for 4Mbyte pages
movl %cr4, %eax
orl $(CR4_PSE), %eax
movl %eax, %cr4
# Use enterpgdir as our initial page table
movl (start−12), %eax
movl %eax, %cr3
# Turn on paging.
movl %cr0, %eax
orl $(CR0_PE|CR0_PG|CR0_WP), %eax
movl %eax, %cr0

# Switch to the stack allocated by startothers()
movl (start−4), %esp
# Call mpenter()
call *(start−8)
```

entryother.S

```
# Turn on page size extension for 4Mbyte pages
movl %cr4, %eax
orl $(CR4_PSE), %eax
movl %eax, %cr4
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entryother.S

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movl %eax, %cr3
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entryother.S

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# Switch to the stack allocated by startothers()
movl (start−4), %esp
# Call mpenter()
call *(start−8)
```

entryother.S

```
static void
mpenter(void)
{
  switchkvm();
  seginit();
  lapicinit();
  mpmain();
}
```

Init segments

```c
static void
mpenter(void)
{
  switchkvm();
  seginit();
  lapicinit();
  mpmain();
}
```

Init segments

```
seginit(void)
{
  struct cpu *c;

  // Map "logical" addresses to virtual addresses using identity map.
  // Cannot share a CODE descriptor for both kernel and user
  // because it would have to have DPL_USR, but the CPU forbids
  // an interrupt from CPL=0 to DPL=3.
  c = &cpus[cpuid()];
  c->gdt[SEG_KCODE] = SEG(STA_X|STA_R, 0, 0xffffffff, 0);
  c->gdt[SEG_KDATA] = SEG(STA_W, 0, 0xffffffff, 0);
  c->gdt[SEG_UCODE] = SEG(STA_X|STA_R, 0, 0xffffffff, DPL_USER);
  c->gdt[SEG_UDATA] = SEG(STA_W, 0, 0xffffffff, DPL_USER);
  lgdt(c->gdt, sizeof(c->gdt));
}
```

Per-CPU variables

- Variables private to each CPU

Per-CPU variables

- Variables private to each CPU
- Current running process
- Kernel stack for interrupts
  - Hence, TSS that stores that stack

```
struct cpu cpus[NCPU];
```

```c
// Per-CPU state
struct cpu {
  uchar apicid;                // Local APIC ID
  struct context *scheduler;   // swtch() here to enter scheduler
  struct taskstate ts;         // Used by x86 to find stack for interrupt
  struct segdesc gdt[NSEGS];   // x86 global descriptor table
  volatile uint started;       // Has the CPU started?
  int ncli;                    // Depth of pushcli nesting.
  int intena;                  // Were interrupts enabled before pushcli?
  struct proc *proc;           // The process running on this cpu or null
};

extern struct cpu cpus[NCPU];
```

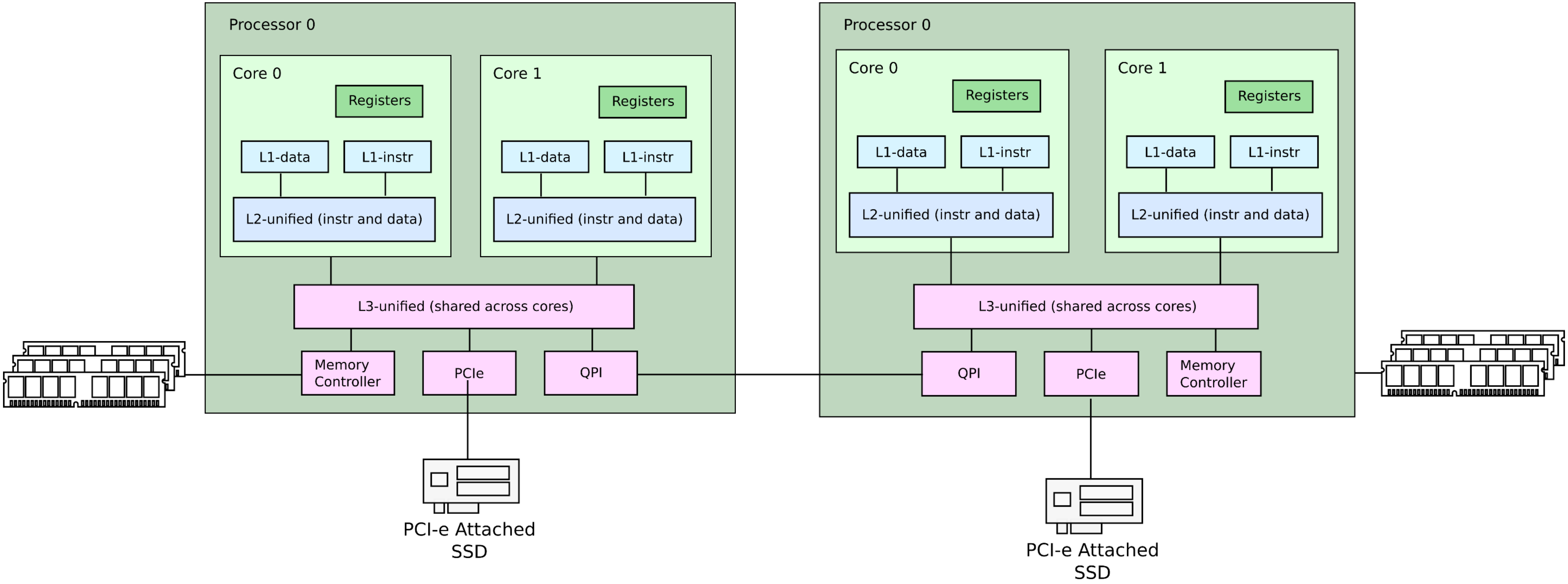
mpmain()

```
// Common CPU setup code.
static void
mpmain(void)
{
  cprintf("cpu%d: starting %d\n", cpuid(), cpuid());
  idtinit();       // load idt register
  xchg(&(mycpu()−>started), 1); // tell startothers() we’re up
  scheduler();     // start running processes
}
```

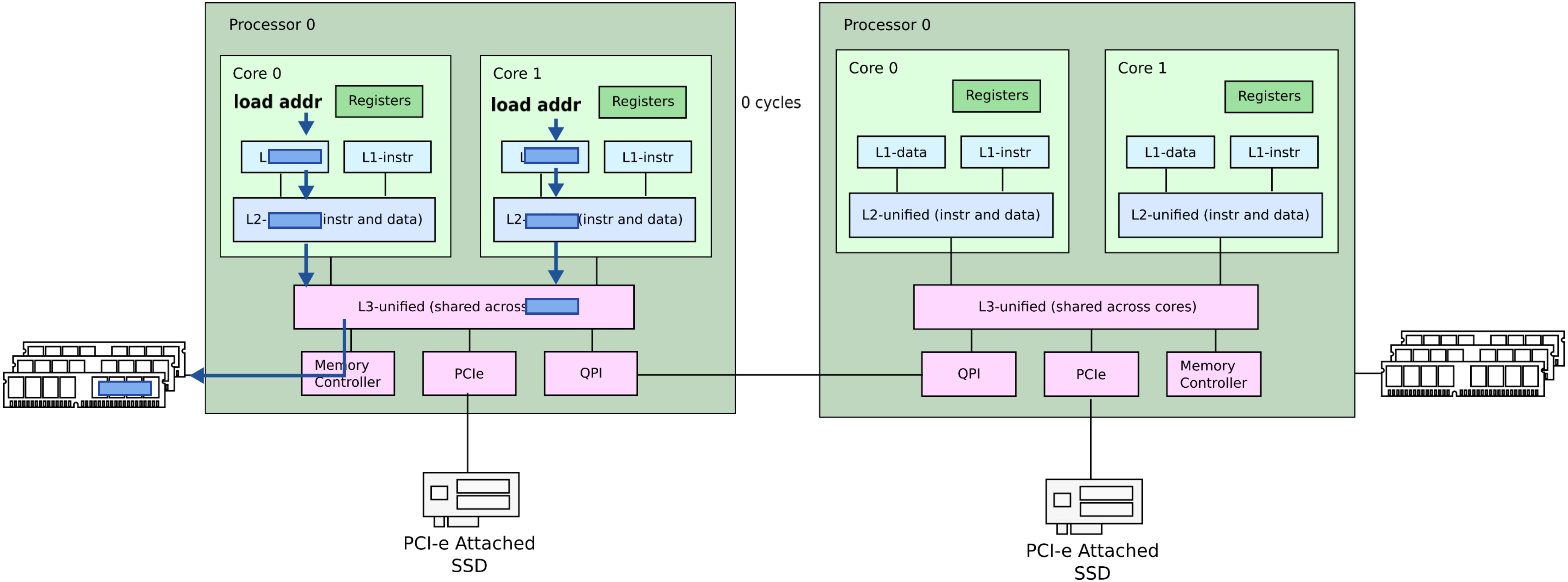
How do CPUs access memory?

Intel Memory Hierarchy

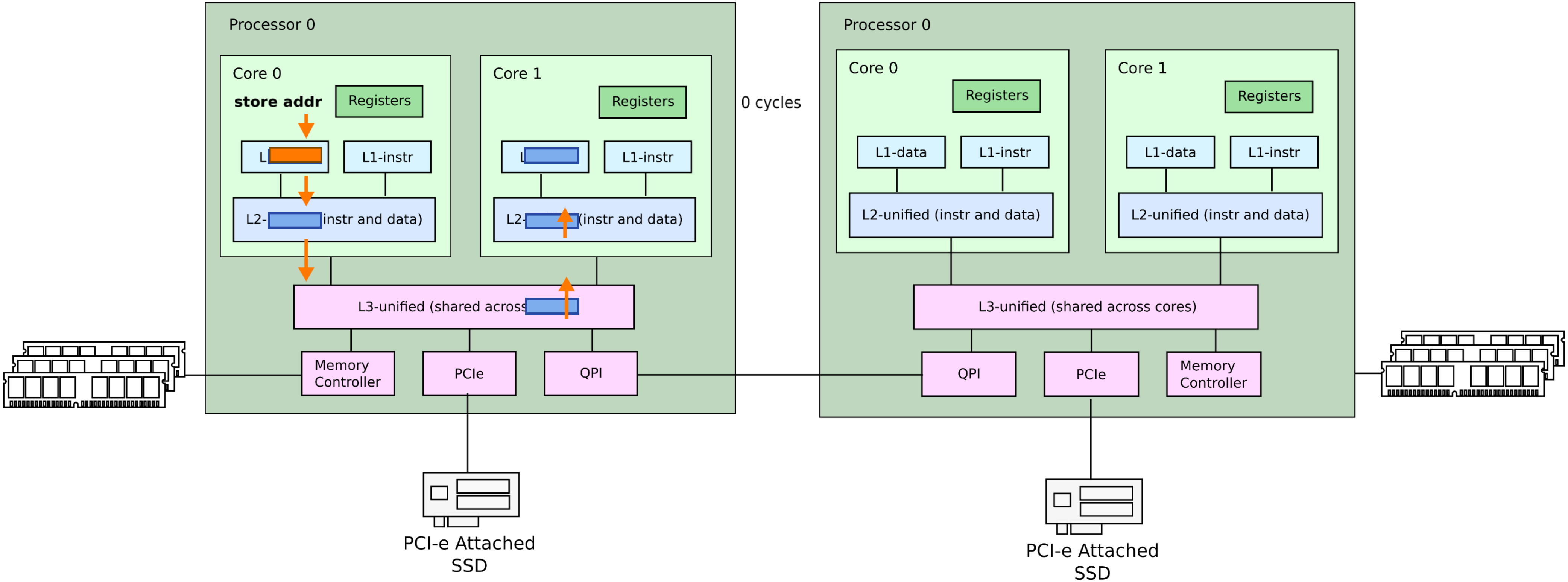
Processors, cores, memory and PCIe



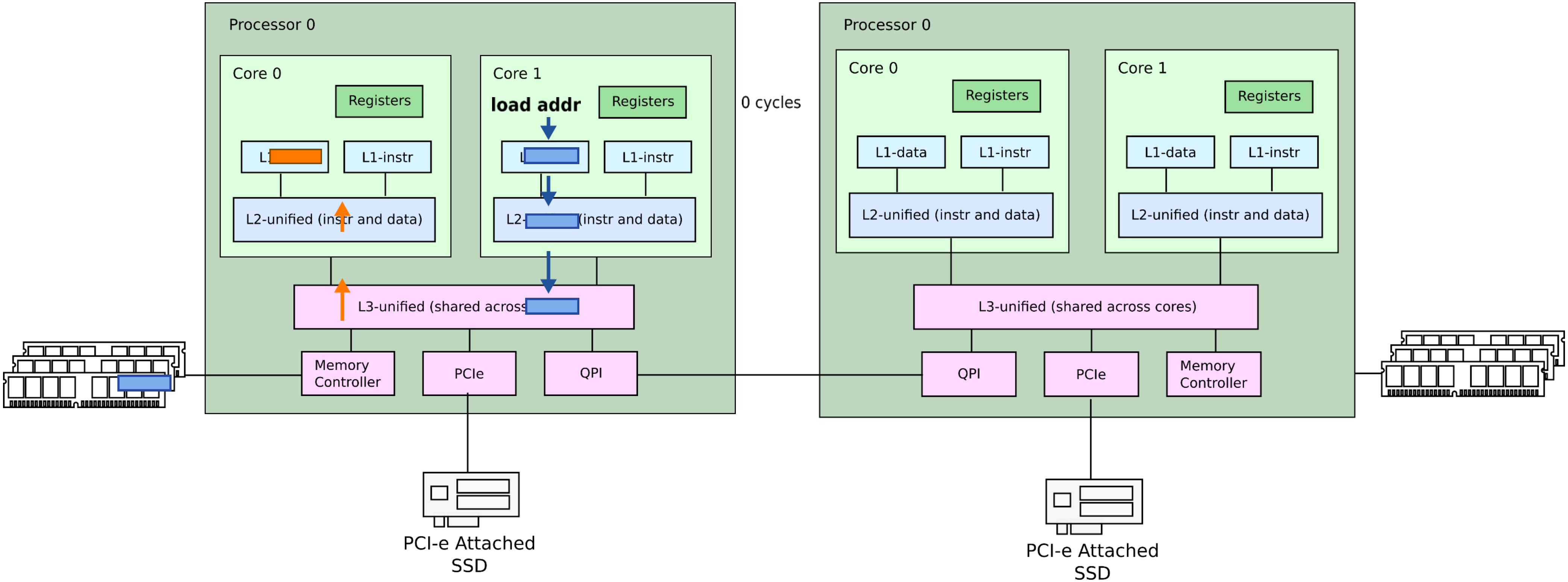
Caches (load)


Processor 0
Core 0
load addr
Registers
L
L1-instr
L2-
instr and data)
Core 1
load addr
Registers
L
L1-instr
L2-
(instr and data)
L3-unified (shared across
Memory
Controller
PCIe
QPI
0 cycles
Processor 0
Core 0
Registers
L1-data
L1-instr
L2-unified (instr and data)
Core 1
Registers
L1-data
L1-instr
L2-unified (instr and data)
L3-unified (shared across cores)
QPI
PCIe
Memory
Controller
PCI-e Attached
SSD
PCI-e Attached
SSD

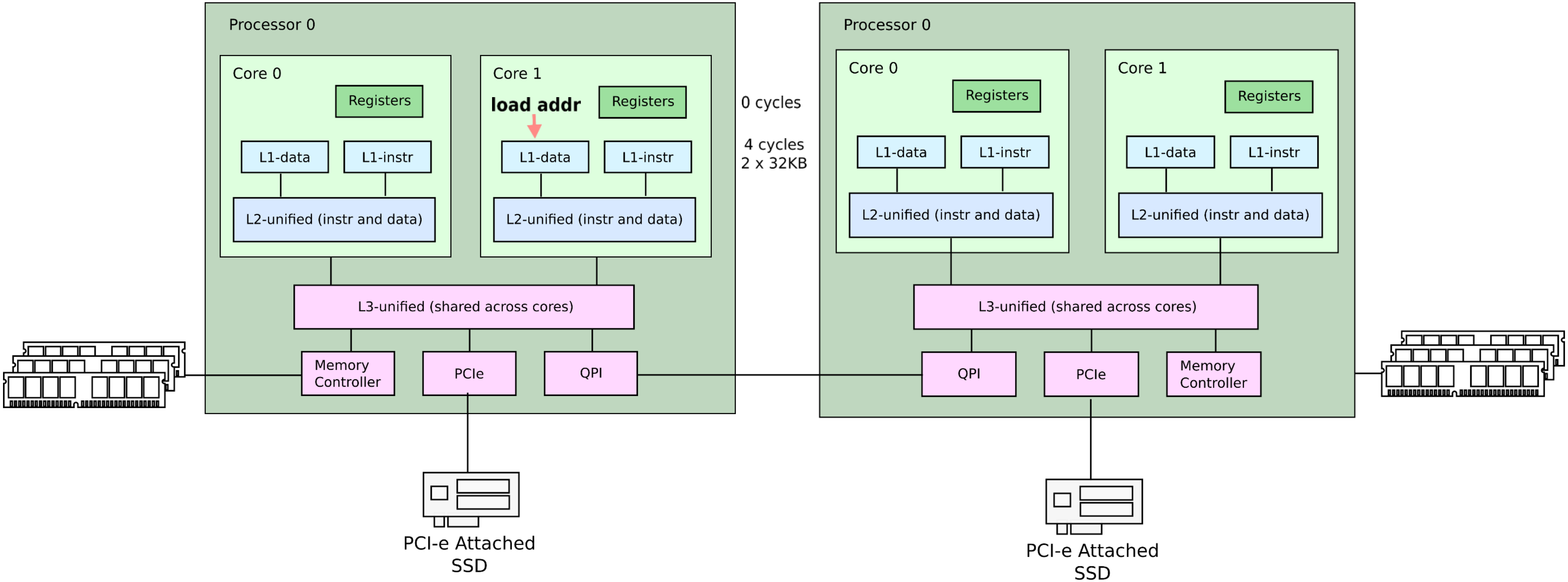
Cache-coherence (store)



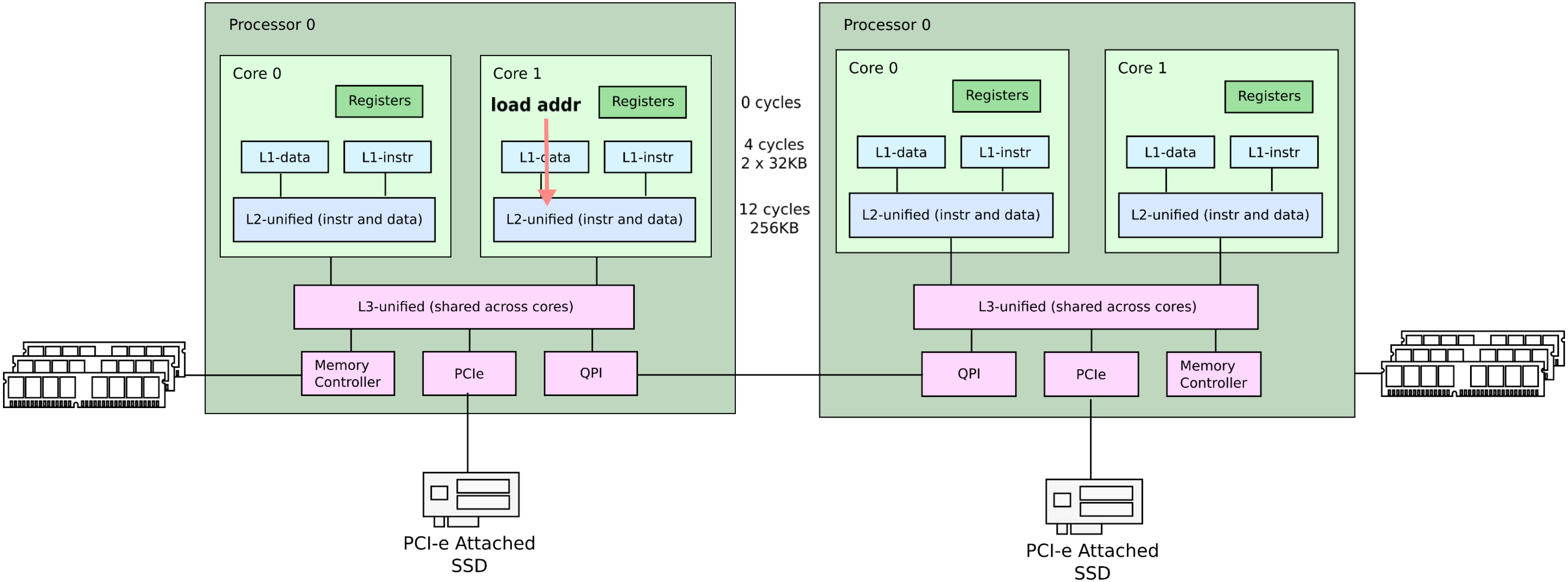
Cache-coherence (load of modified)



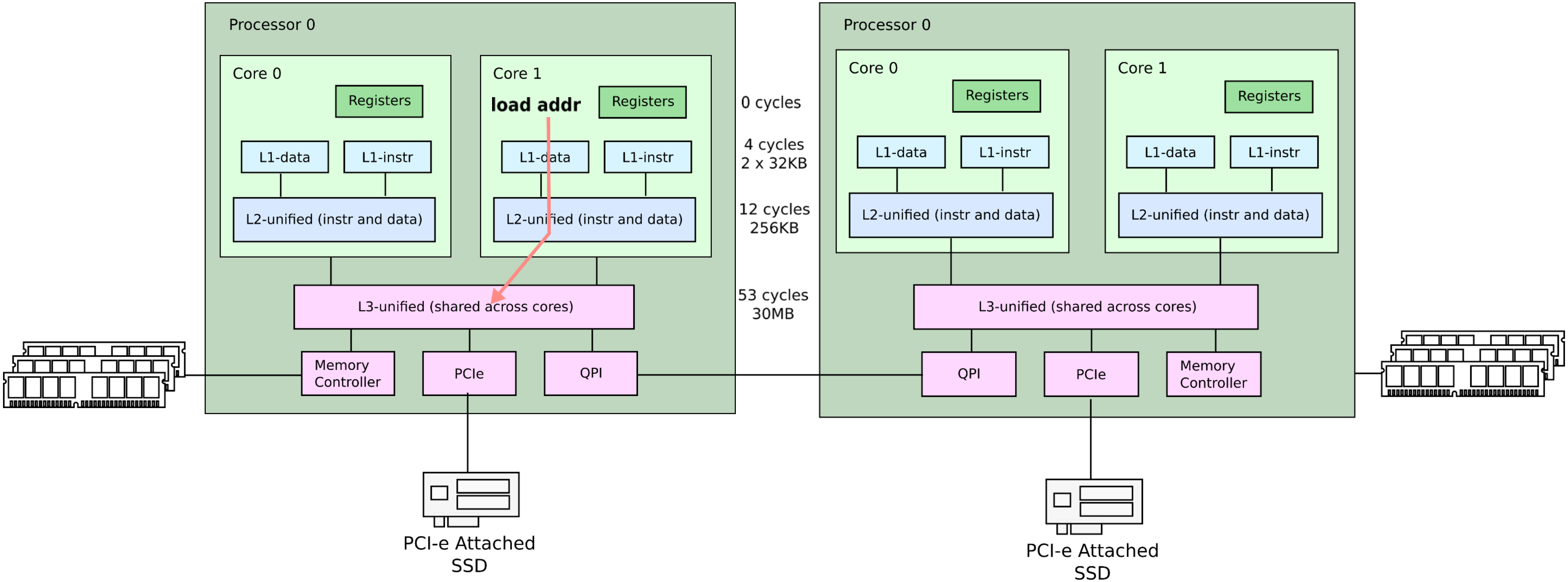
Latencies: load from local L1



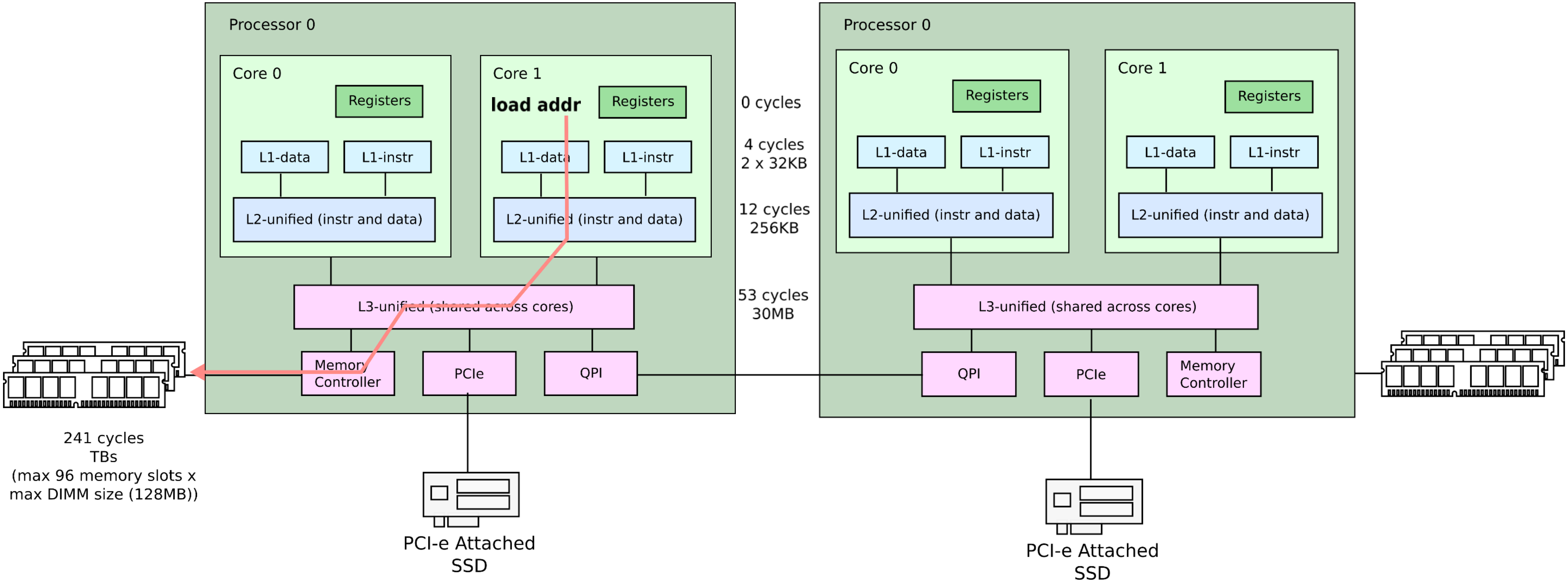
Latencies: load from local L2



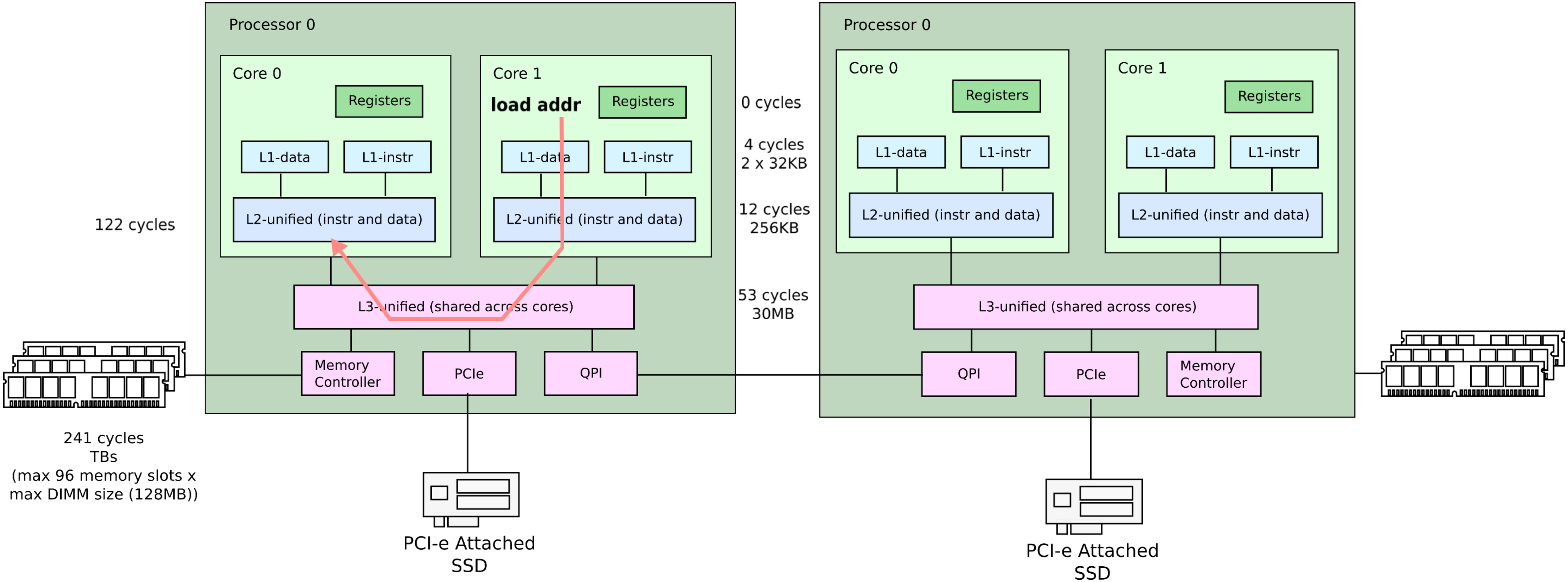
Latencies: load from local L3



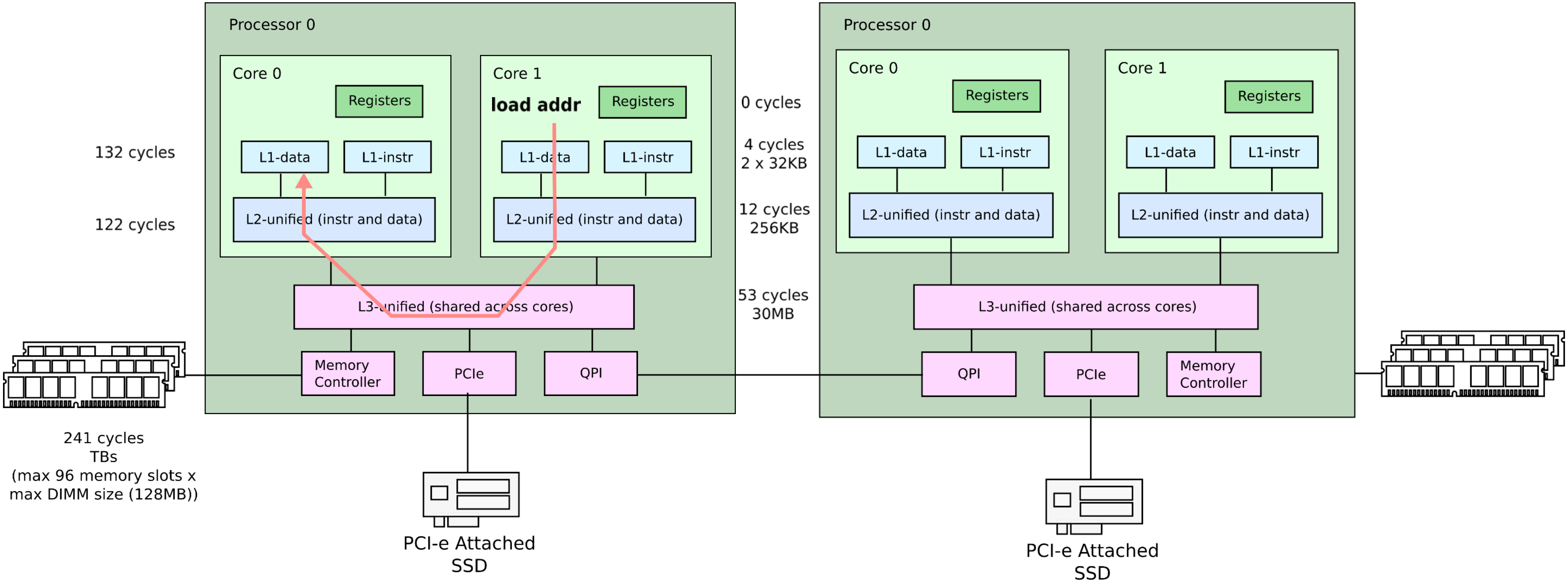
Latencies: load from local memory



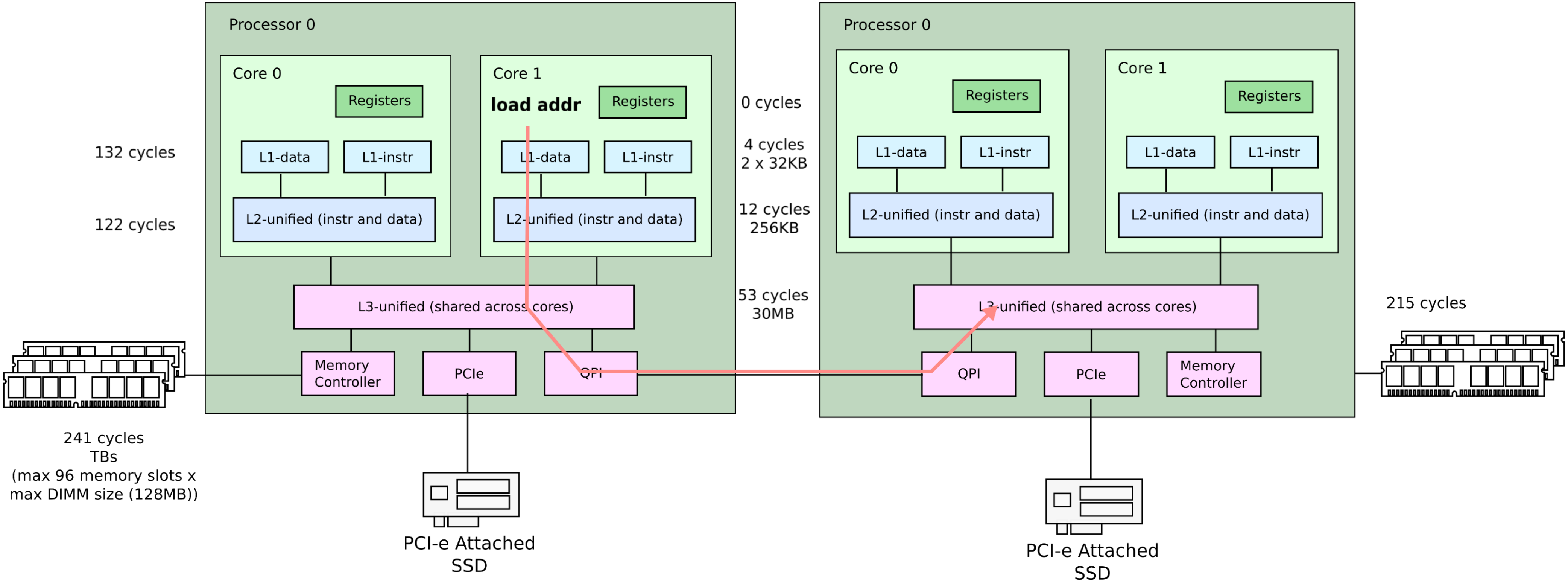
Latencies: load from same die core's L2



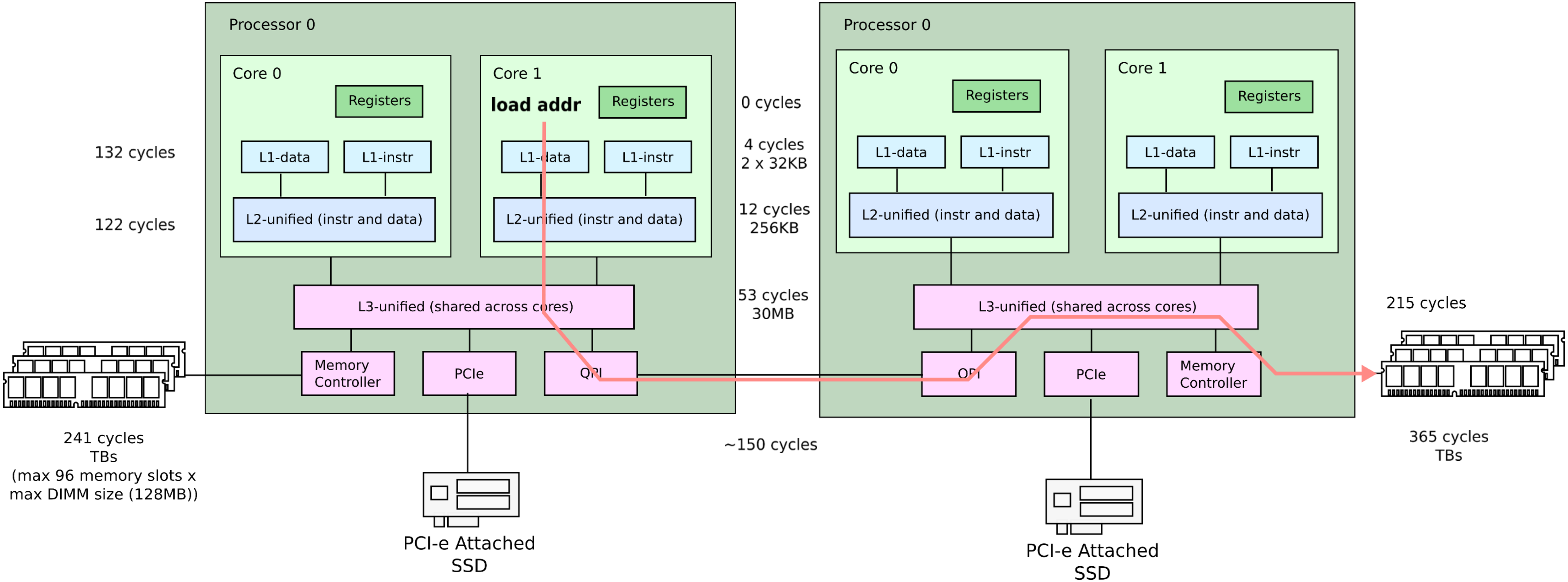
Latencies: load from same die core's L1



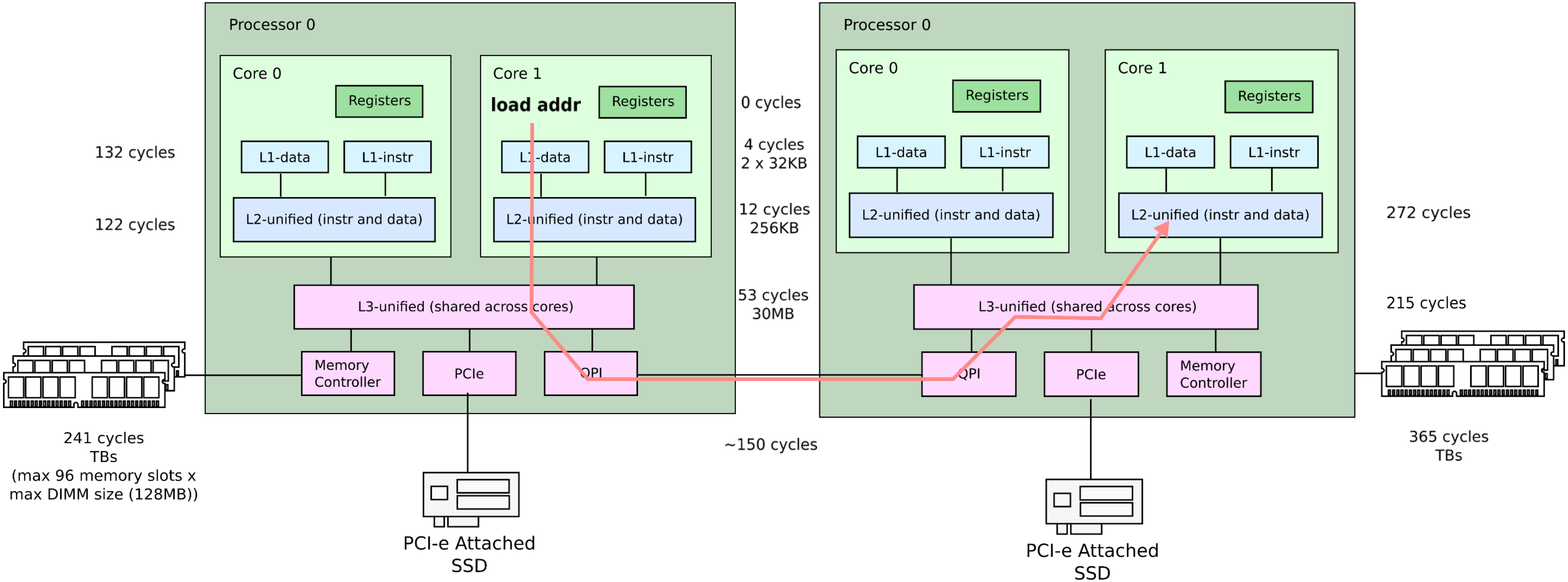
Latencies: load from remote L3



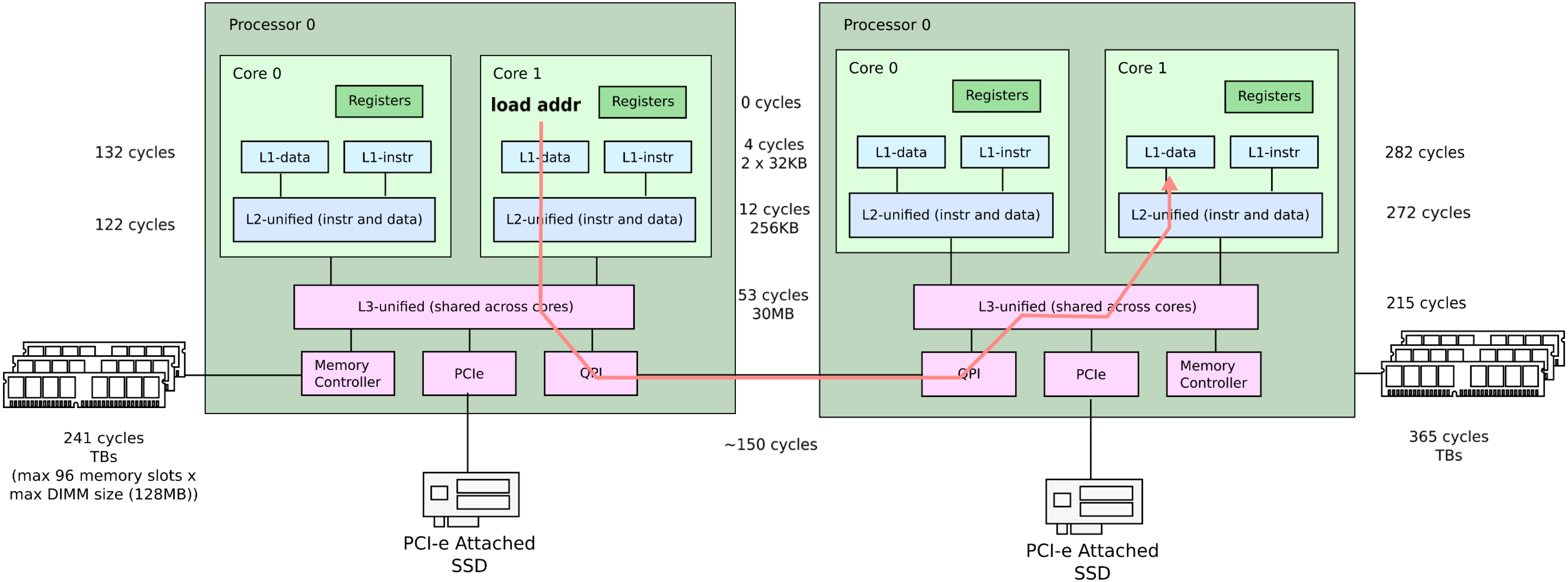
Latencies: load from remote memory



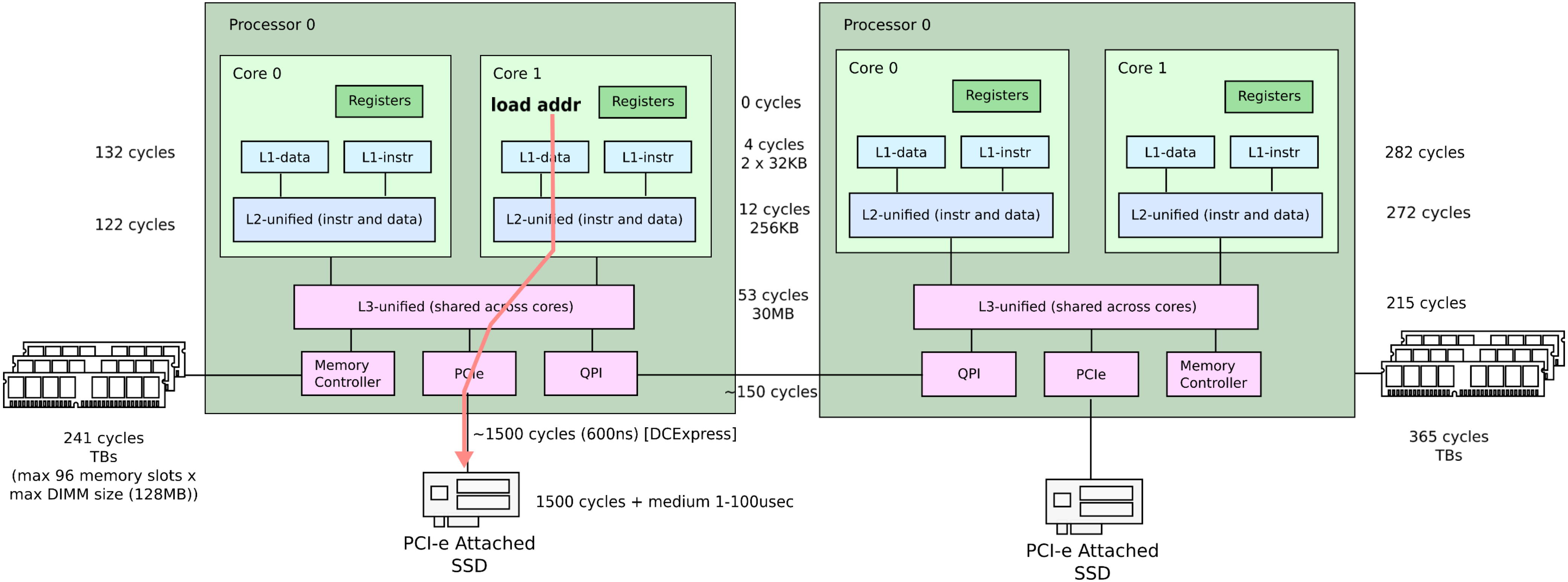
Latencies: load from remote L2



Latencies: load from remote L2



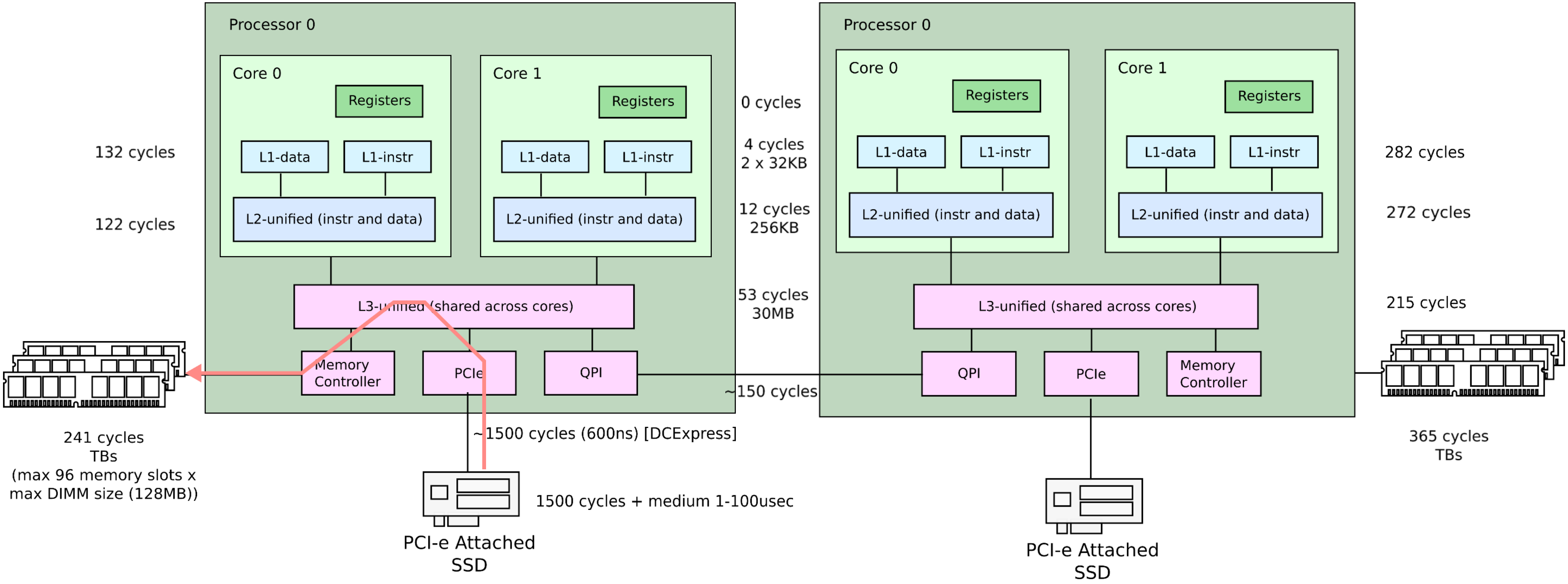
Latencies: PCIe round-trip



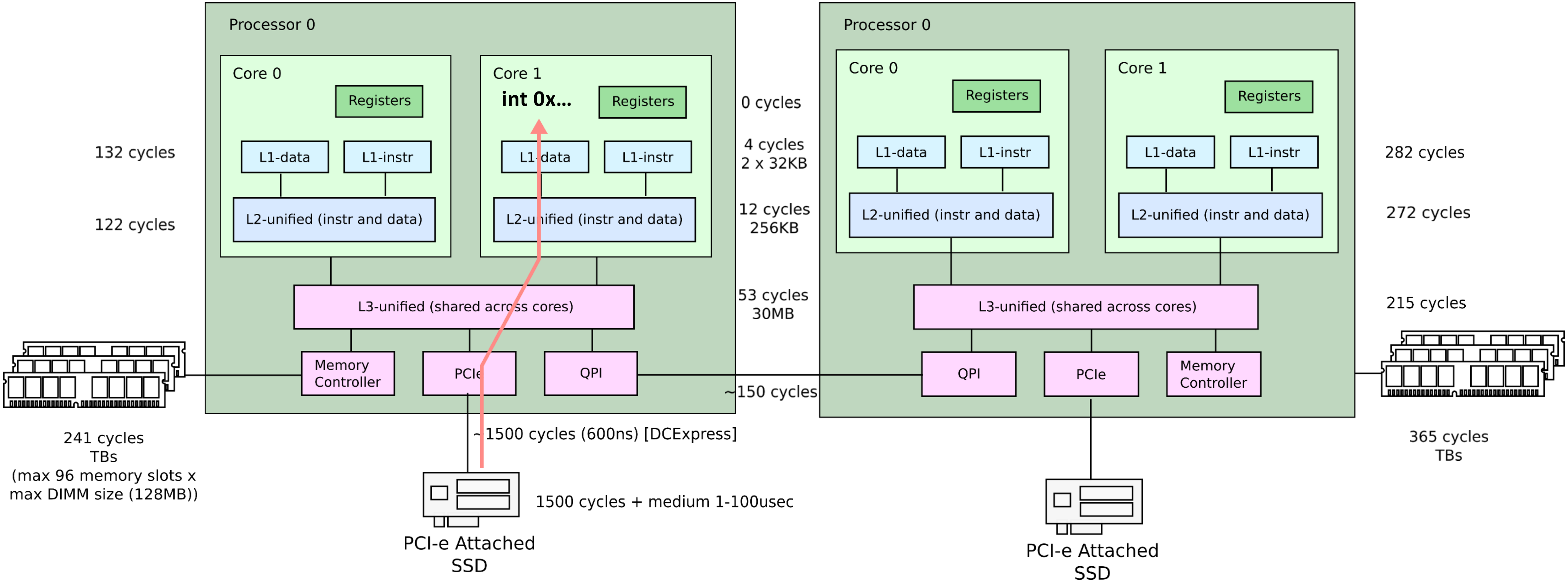
Device I/O

- Essentially just sending data to and from external devices
- Modern devices communicate over PCIe
  - Well there are other popular buses, e.g., USB, SATA (disks), etc.
  - Conceptually they are similar
- Devices can
  - Read memory
  - Send interrupts to the CPU

Direct memory access

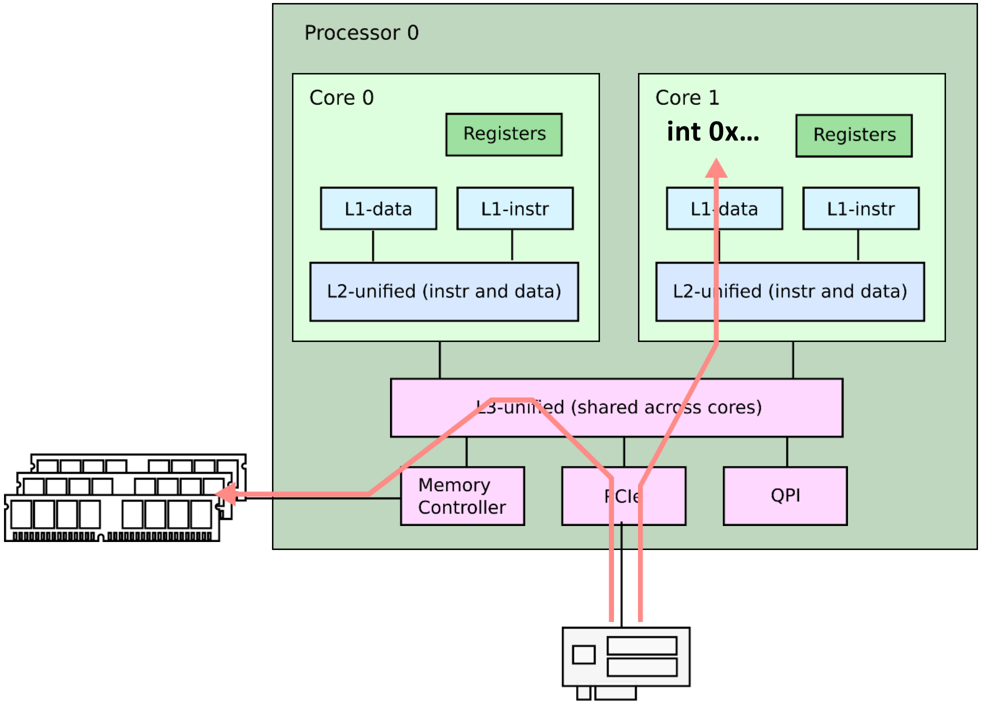


Interrupts



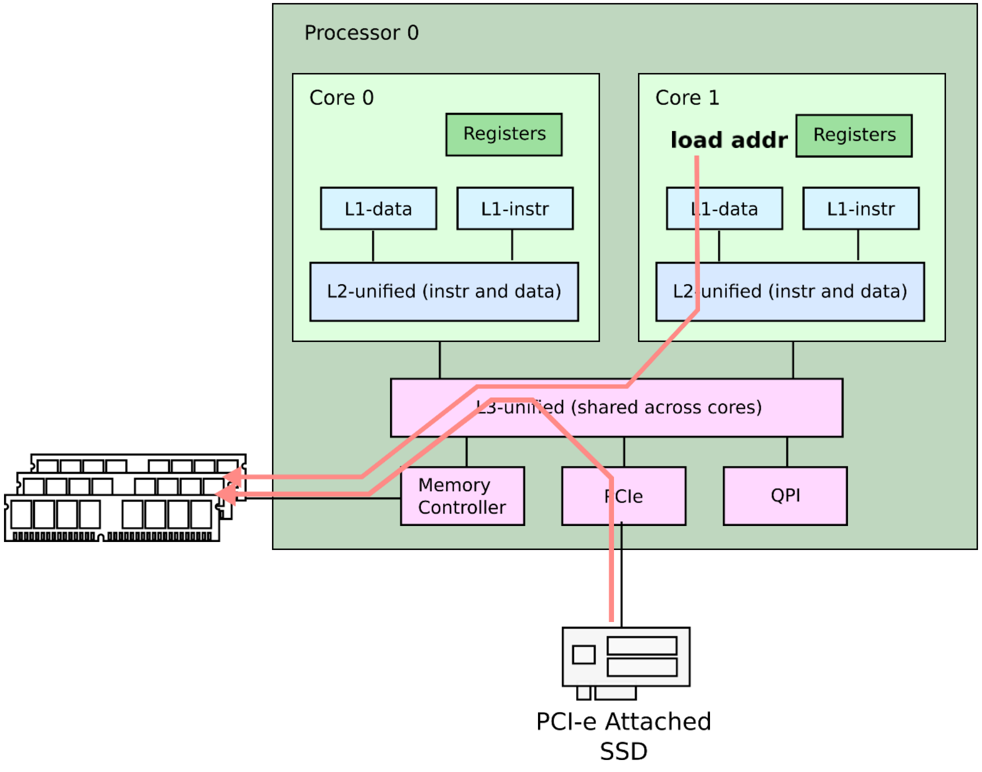
Processor 0
Core 0
Registers
L1-data
L1-instr
L2-unified (instr and data)
Core 1
int 0x...
Registers
L1-data
L1-instr
L2-unified (instr and data)
L3-unified (shared across cores)
Memory Controller
PCIe
QPI
Processor 0
Core 0
Registers
L1-data
L1-instr
L2-unified (instr and data)
Core 1
Registers
L1-data
L1-instr
L2-unified (instr and data)
L3-unified (shared across cores)
QPI
PCIe
Memory Controller
132 cycles
122 cycles
0 cycles
4 cycles
2 x 32KB
12 cycles
256KB
53 cycles
30MB
~150 cycles
282 cycles
272 cycles
215 cycles
241 cycles
TBs
(max 96 memory slots x
max DIMM size (128MB))
~1500 cycles (600ns) [DCExpress]
1500 cycles + medium 1-100usec
PCI-e Attached
SSD
PCI-e Attached
SSD
365 cycles
TBs

Device I/O



- Write incoming data in memory, e.g.,
  - Network packets
  - Disk requests, etc.
- Then raise an interrupt to notify the CPU
  - CPU starts executing interrupt handler
  - Then reads incoming packets form memory

Device I/O (polling mode)



- Alternatively the CPU has to check for incoming data in memory periodically
  - Or poll
- Rationale
  - Interrupts are expensive

References

- Cache Coherence Protocol and Memory Performance of the Intel Haswell-EP Architecture. http://ieeexplore.ieee.org/abstract/document/7349629
- Intel SGX Explained https://eprint.iacr.org/2016/086.pdf
- DC Express: Shortest Latency Protocol for Reading Phase Change Memory over PCI Express https://www.usenix.org/system/files/conference/fast14/fast14-paper_vucinic.pdf

End of detour: Cache-coherence and memory hierarchy

Synchronization

Race conditions

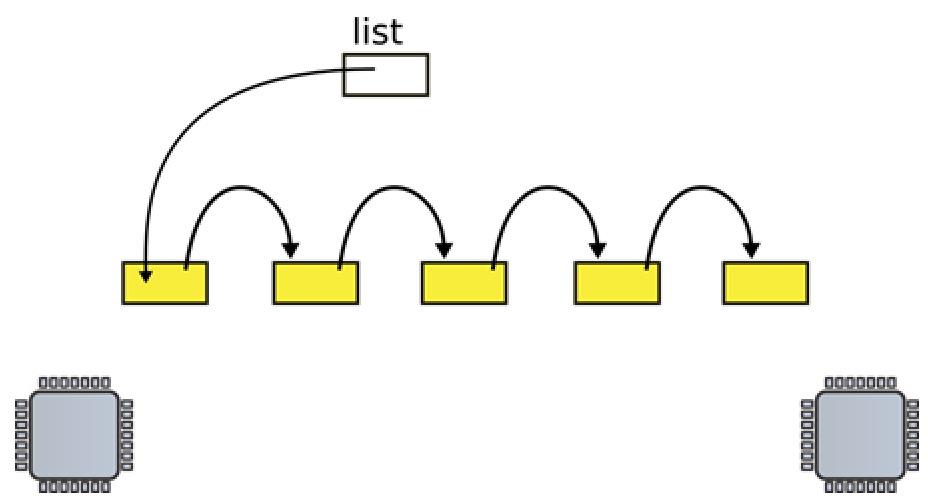
- Example:
- Disk driver maintains a list of outstanding requests
- Each process can add requests to the list

List implementation (no locks)

```
struct list {
  int data;
  struct list *next;
};
...
struct list *list = 0;
...
insert(int data)
{
  struct list *l;

  l = malloc(sizeof *l);
  l->data = data;
  l->next = list;
  list = l;
}
```

- List
  - One data element
  - Pointer to the next element



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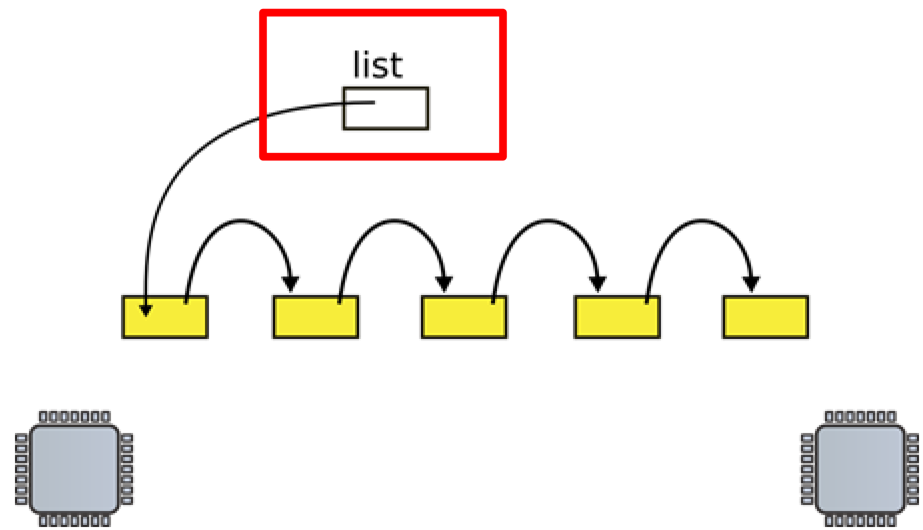
  l = malloc(sizeof *l);
  l->data = data;
  l->next = list;
  list = l;
}
```

- Global head



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  list = l;
}
```
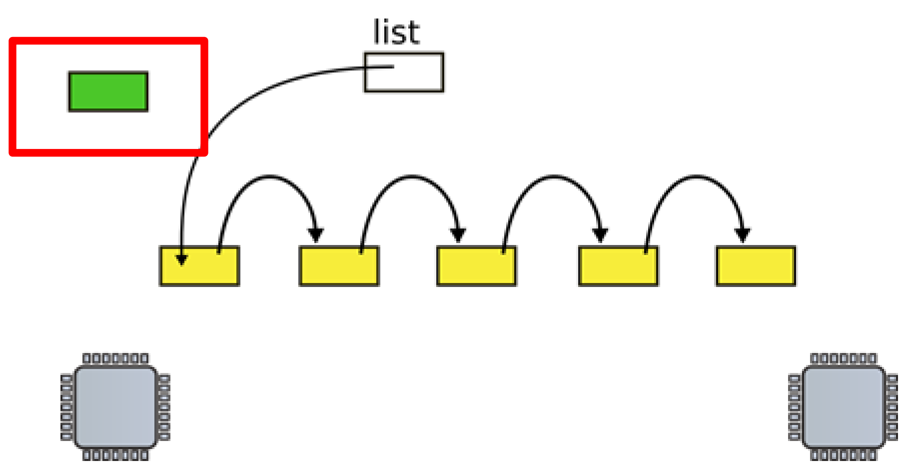

- Insertion
  - Allocate new list element



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  l->data = data;
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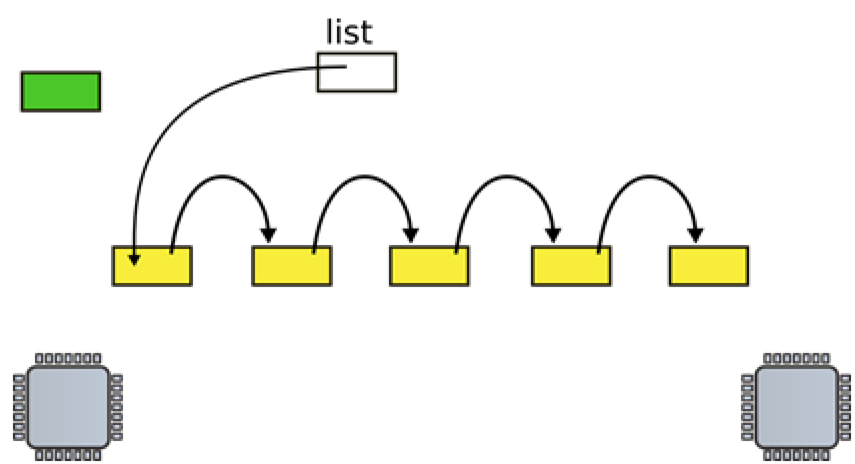
```

List implementation (no locks)

- Insertion
  - Allocate new list element
  - Save data into that element



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  l->data = data;
  l->next = list;
  list = l;
}
```
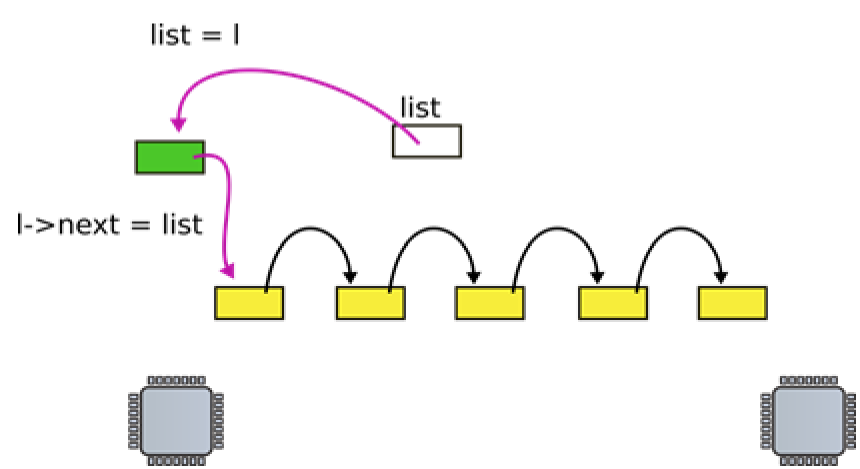
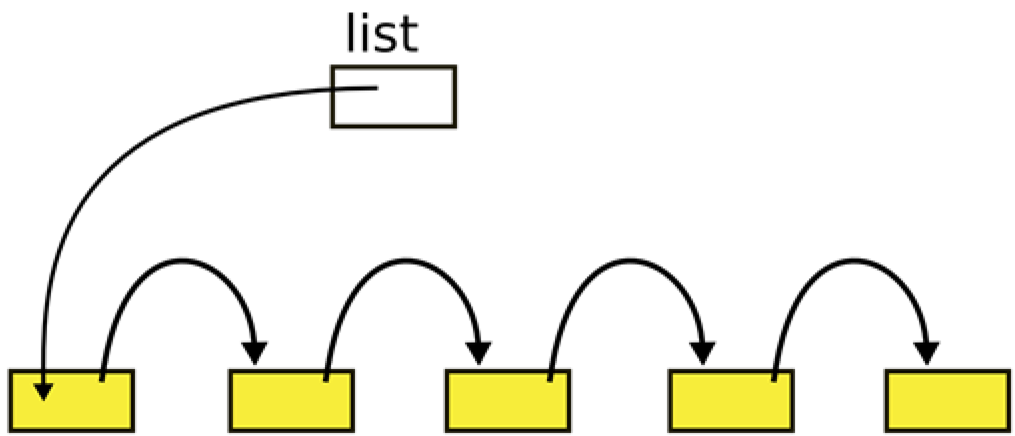
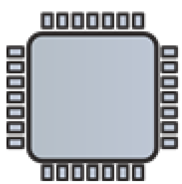

- Insertion
  - Allocate new list element
  - Save data into that element
  - Insert into the list

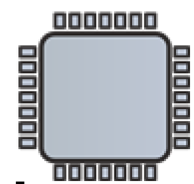


Now what happens when two CPUs access the same list

Request queue (e.g. pending disk requests)

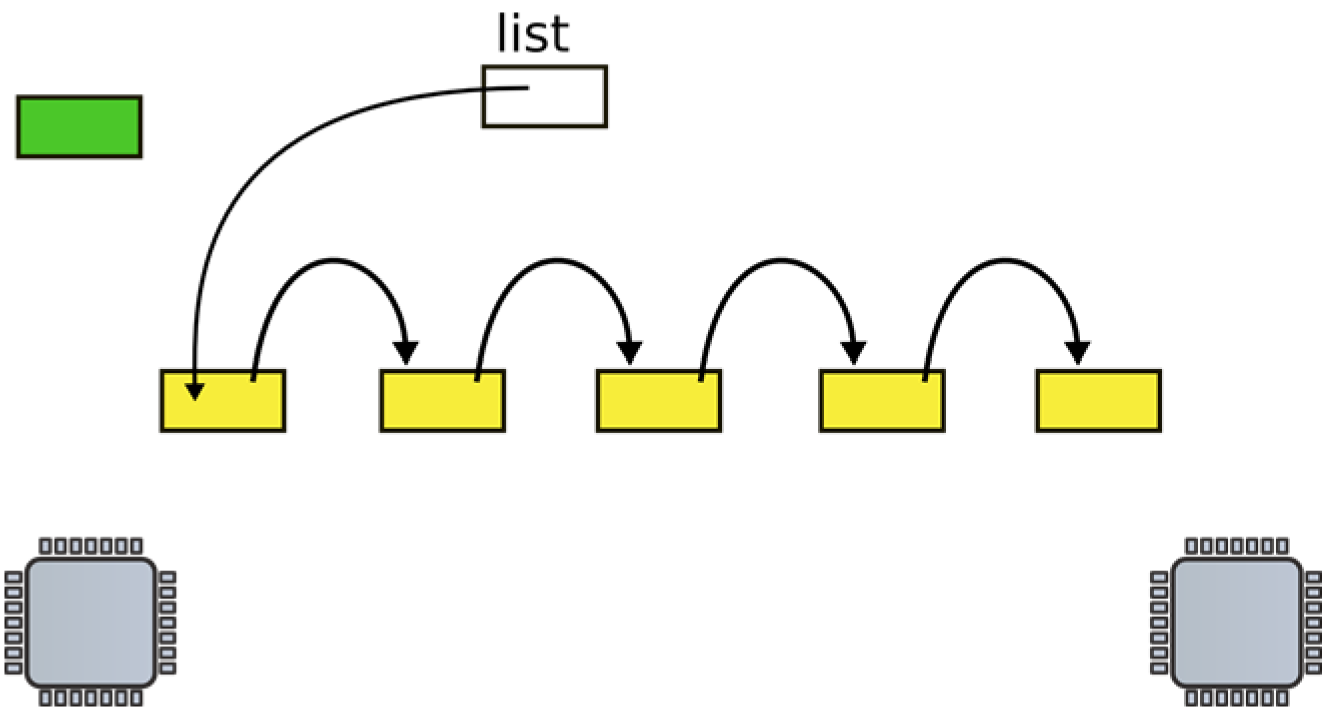




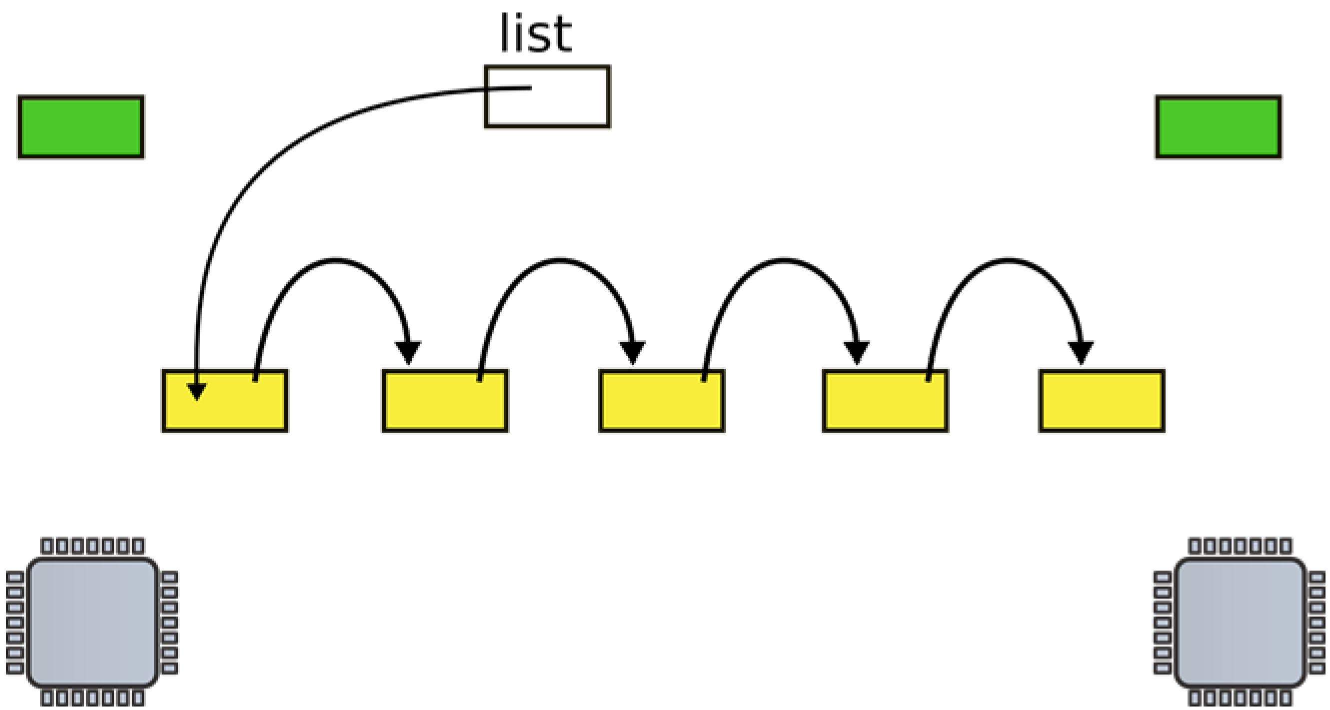


- Linked list, list is pointer to the first element

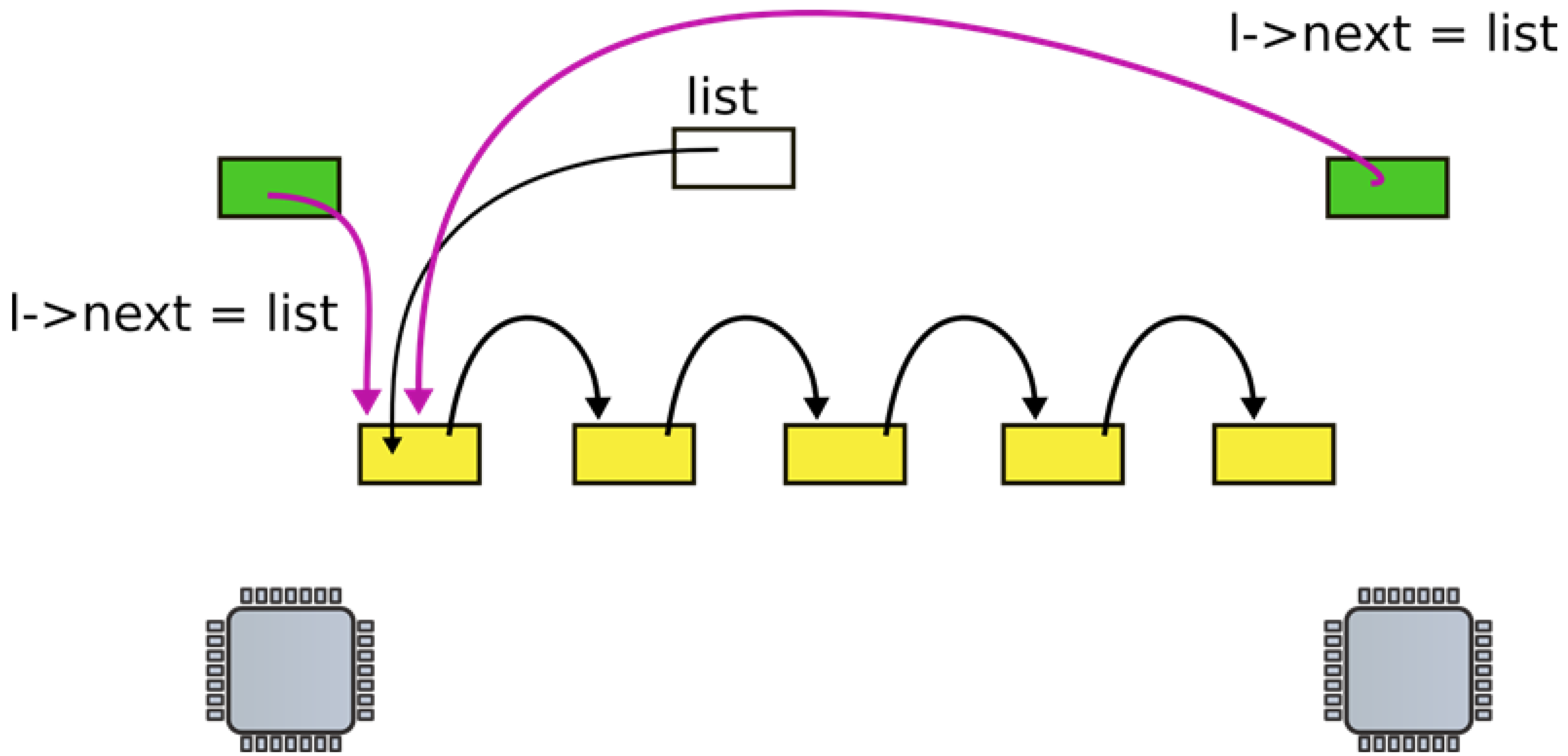
CPU1 allocates new request



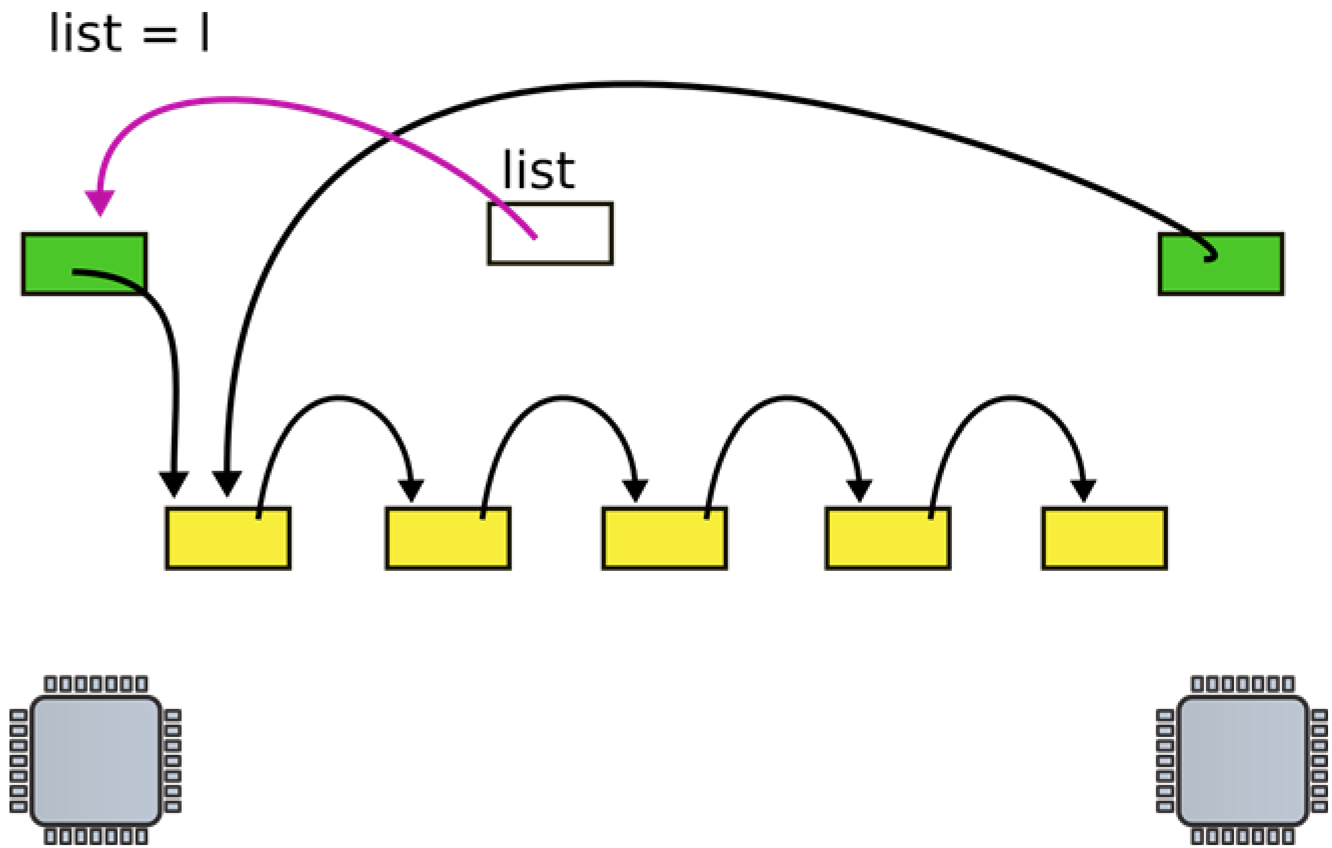
CPU2 allocates new request



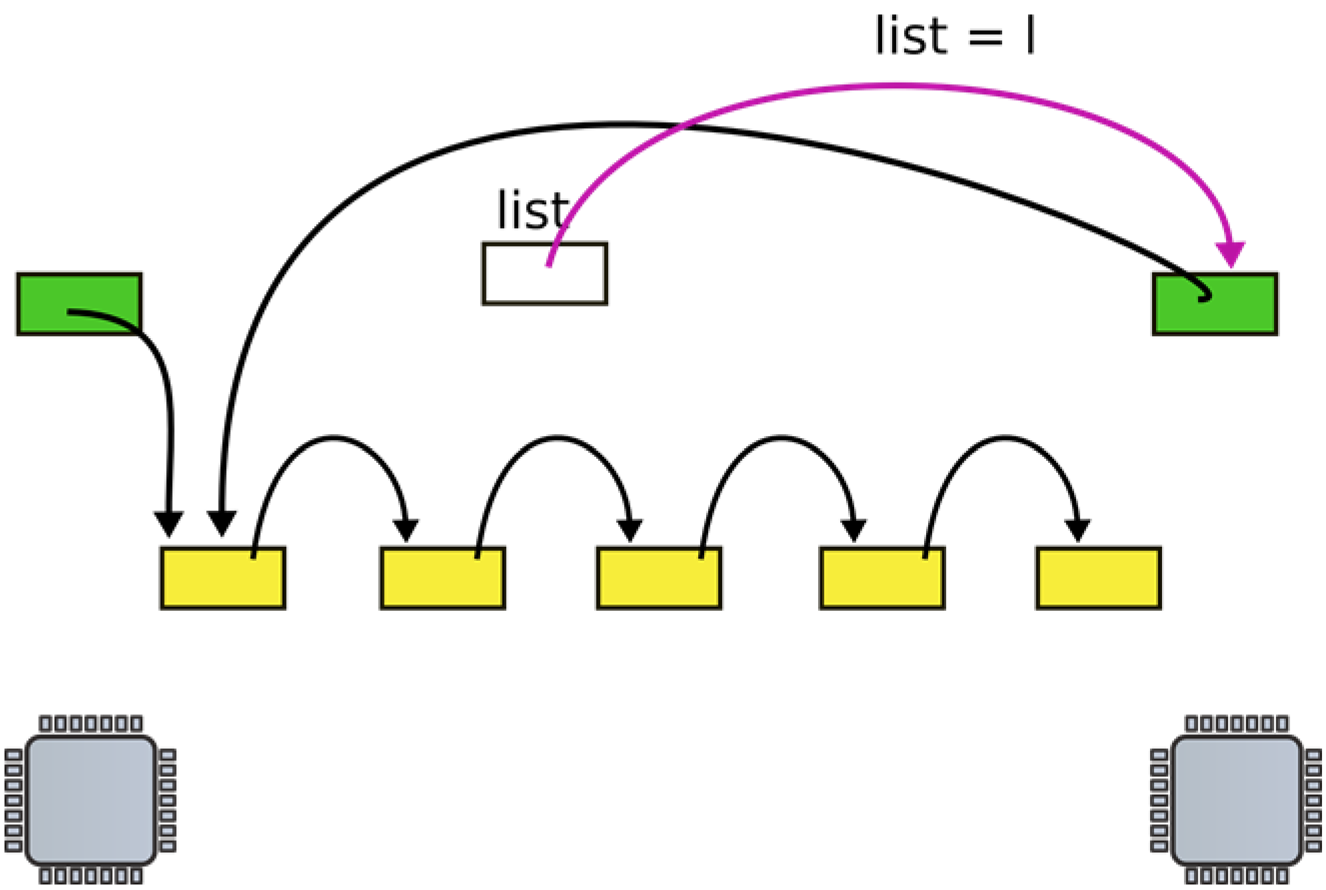
CPUs 1 and 2 update next pointer



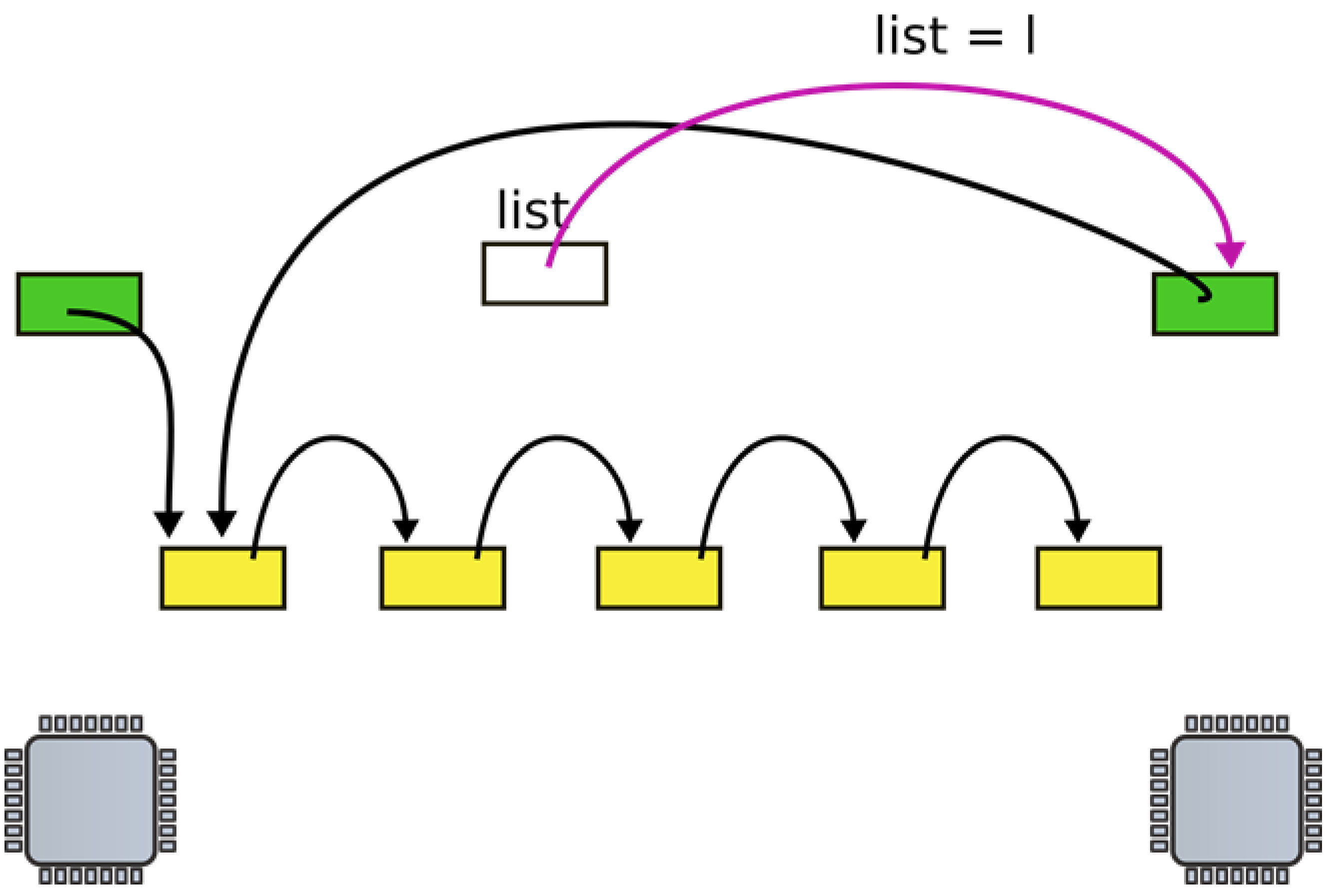
CPU1 updates head pointer



CPU2 updates head pointer

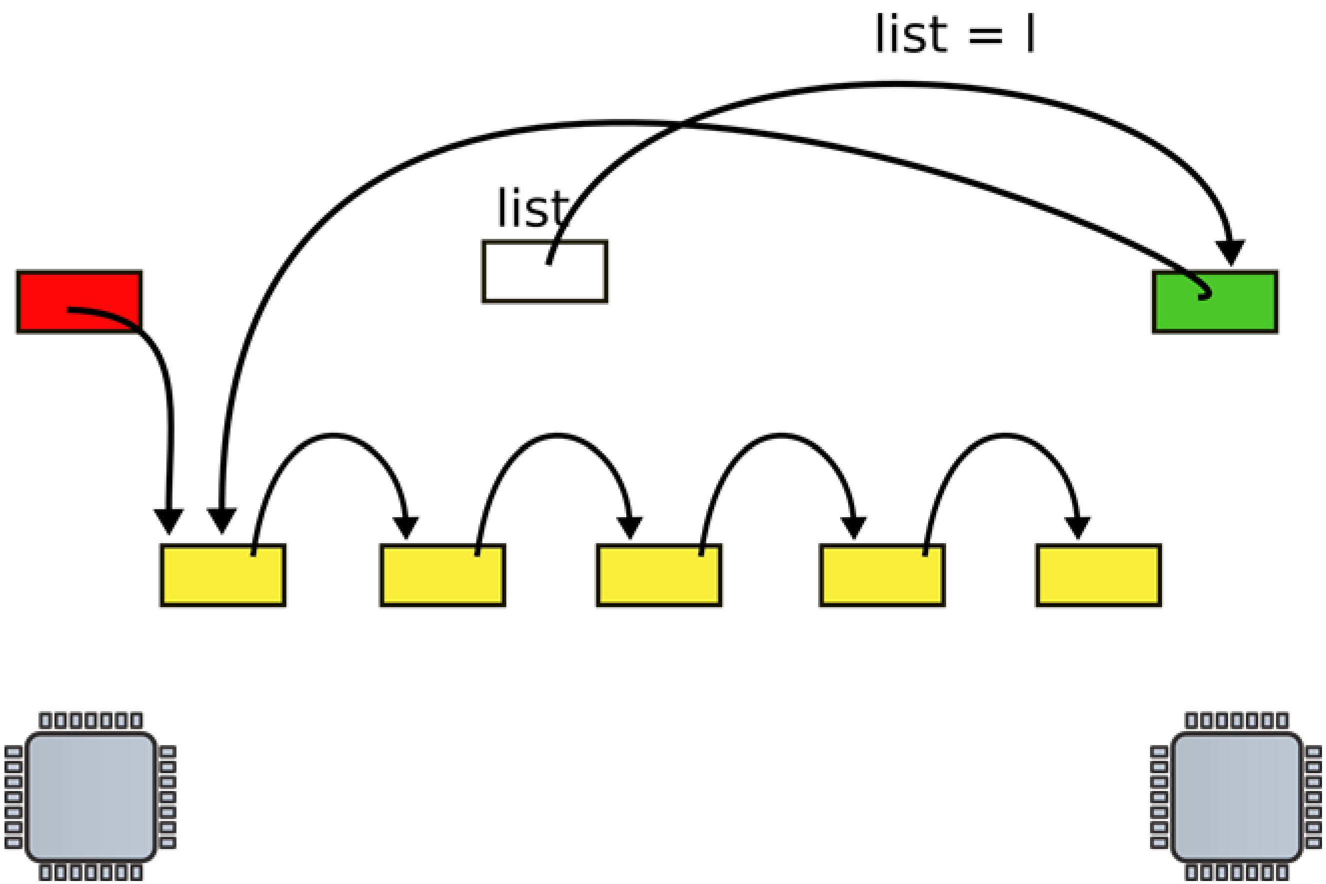


CPU2 updates head pointer



- Is everything ok? Poll: PollEv.com/antonburtsev

State after the race (red element is lost)



Mutual exclusion

- Only one CPU can update list at a time

List implementation with locks

```
struct list {
  int data;
  struct list *next;
};
struct list *list = 0;
 struct lock listlock;
insert(int data)
{
  struct list *l;
  l = malloc(sizeof *l);
  acquire(&listlock);
  l->data = data;
  l->next = list;
  list = l;
  release(&listlock);
}
```

- Critical section

- How can we implement acquire()?

Spinlock

```
void
acquire(struct spinlock *lk)
{
  for(;;) {
    if(!lk->locked) {
      lk->locked = 1;
      break;
    }
  }
}
```

- Spin until lock is 0
- Set it to 1

Still incorrect

```
21 void
22 acquire(struct spinlock *lk)
23 {
24   for(;;) {
25     if(!lk->locked) {
26       lk->locked = 1;
27       break;
28     }
29   }
30 }
```

- Two CPUs can reach line #25 at the same time
- See not locked, and
- Acquire the lock
- Lines #25 and #26 need to be atomic

Compare and swap: xchg

- Swap a word in memory with a new value
- Return old value

Correct implementation

```
void
acquire(struct spinlock *lk)
{
...
  // The xchg is atomic.
  while(xchg(&lk−>locked, 1) != 0)
    ;
...
}
```

xchg instruction

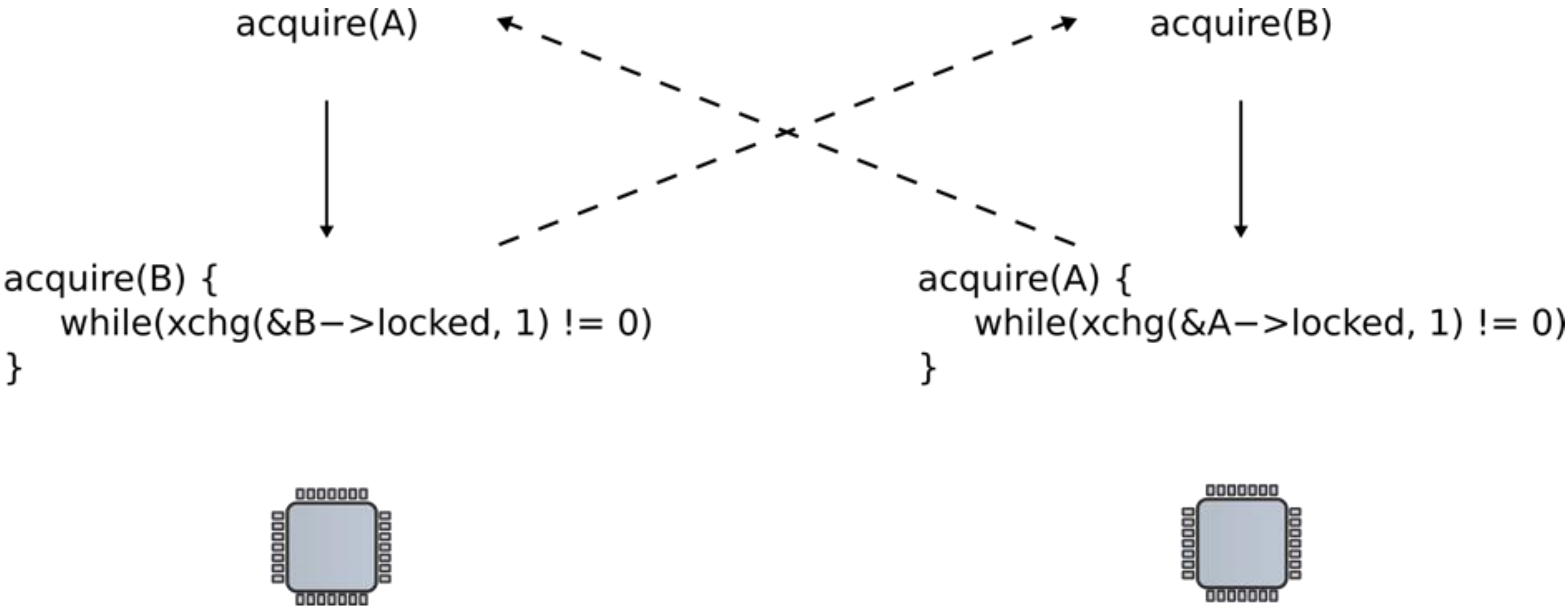
```
static inline uint
xchg(volatile uint *addr, uint newval)
{
  uint result;

  // The + in "+m" denotes a read−modify−write operand.
  asm volatile("lock; xchgl %0, %1" :
               "+m" (*addr), "=a" (result) :
               "1" (newval) :
               "cc");
  return result;
}
```

Correct implementation

```
void
acquire(struct spinlock *lk)
{
...
  // The xchg is atomic.
  while(xchg(&lk->locked, 1) != 0)
    ;
  // Tell the C compiler and the processor to not move loads or stores
  // past this point, to ensure that the critical section's memory
  // references happen after the lock is acquired.
  __sync_synchronize();
...
}
```

Deadlocks

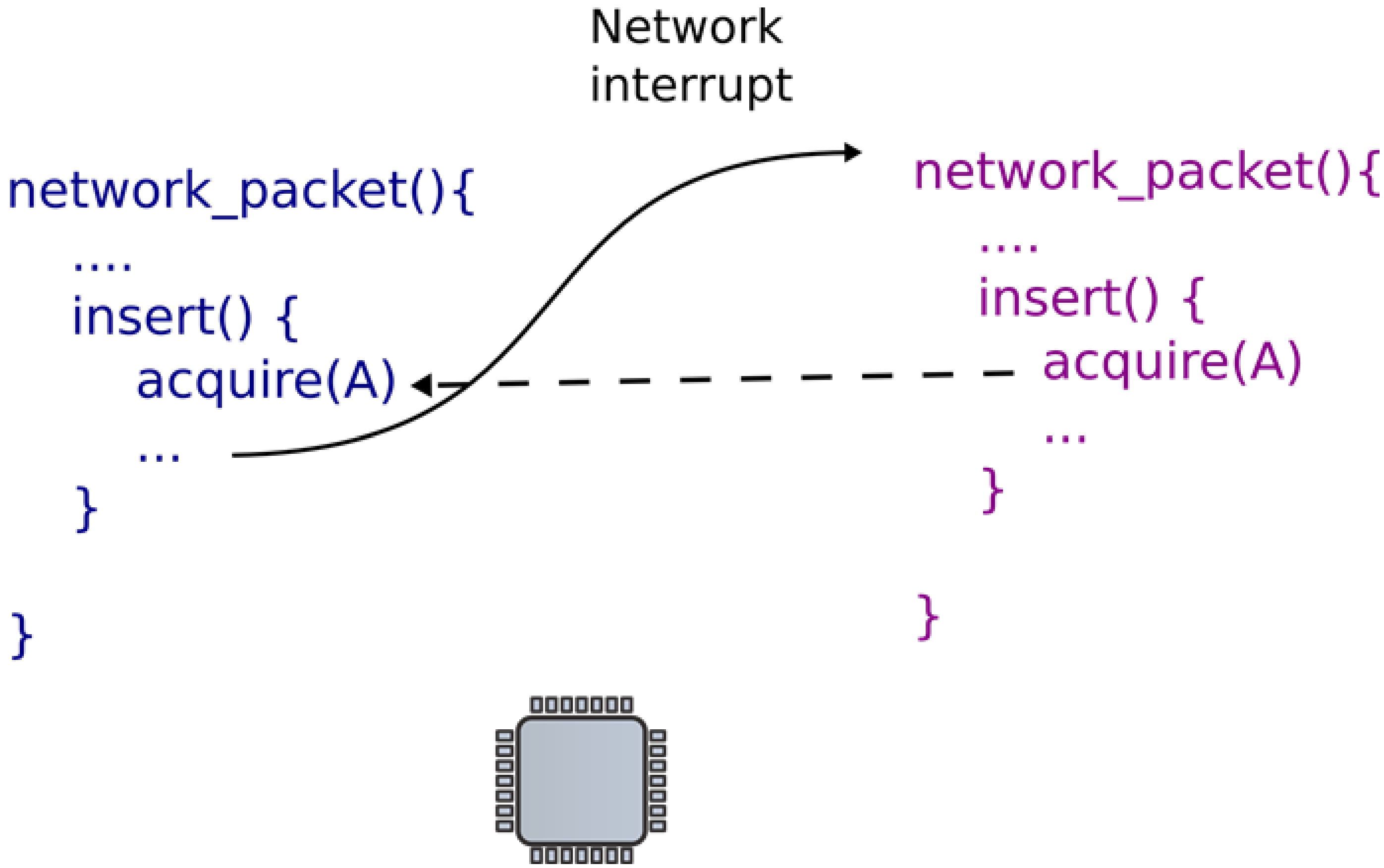
Deadlocks


acquire(A)
acquire(B)
acquire(B) {
while(xchg(&B−>locked, 1) != 0)
}
acquire(A) {
while(xchg(&A−>locked, 1) != 0)
}

Lock ordering

- Locks need to be acquired in the same order

Locks and interrupts



Locks and interrupts

- Never hold a lock with interrupts enabled

Disabling interrupts

```
void
acquire(struct spinlock *lk)
{
  pushcli(); // disable interrupts to avoid deadlock.
  if(holding(lk))
    panic("acquire");
  // The xchg is atomic.
  while(xchg(&lk->locked, 1) != 0)
    ;
...
  __sync_synchronize();
...
}
```

Simple disable/enable is not enough

- If two locks are acquired
- Interrupts should be re-enabled only after the second lock is released

- Pushcli() uses a counter

Pushcli()/popcli()

```
pushcli(void)
{
  int eflags;

  eflags = readeflags();
  cli();
  if(cpu->ncli == 0)
    cpu->intena = eflags & FL_IF;
  cpu->ncli += 1;
}
```

Pushcli()/popcli()

```
popcli(void)
{
  if(readeflags()&FL_IF)
    panic("popcli − interruptible");
  if(−−cpu−>ncli < 0)
    panic("popcli");
  if(cpu−>ncli == 0 && cpu−>intena)
    sti();
}
```

Locks and interprocess communication

Send/receive queue

```
struct q {
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    ;
  q->ptr = 0;
  return p;
}
```

- Sends one pointer between two CPUs

Send/receive queue

```
struct q {
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    ;
  q->ptr = 0;
  return p;
}
```

Send/receive queue

```
struct q {
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    ;
  q->ptr = 0;
  return p;
}
```

Send/receive queue

```
struct q {
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    ;
  q->ptr = 0;
  return p;
}
```

- Poll: https://pollev.com/antonburtsev

Send/receive queue

```
struct q {
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    ;
  q->ptr = 0;
  return p;
}
```

- Works well, but expensive if communication is rare
- Receiver wastes CPU cycles

Sleep and wakeup

- sleep(channel)
  - Put calling process to sleep
  - Release CPU for other work
- wakeup(channel)
  - Wakes all processes sleeping on a channel if any
  - i.e., causes sleep() calls to return

Send/receive queue

```
void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
  wakeup(q); /*wake recv*/
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    sleep(q);
  q->ptr = 0;
  return p;
}
```

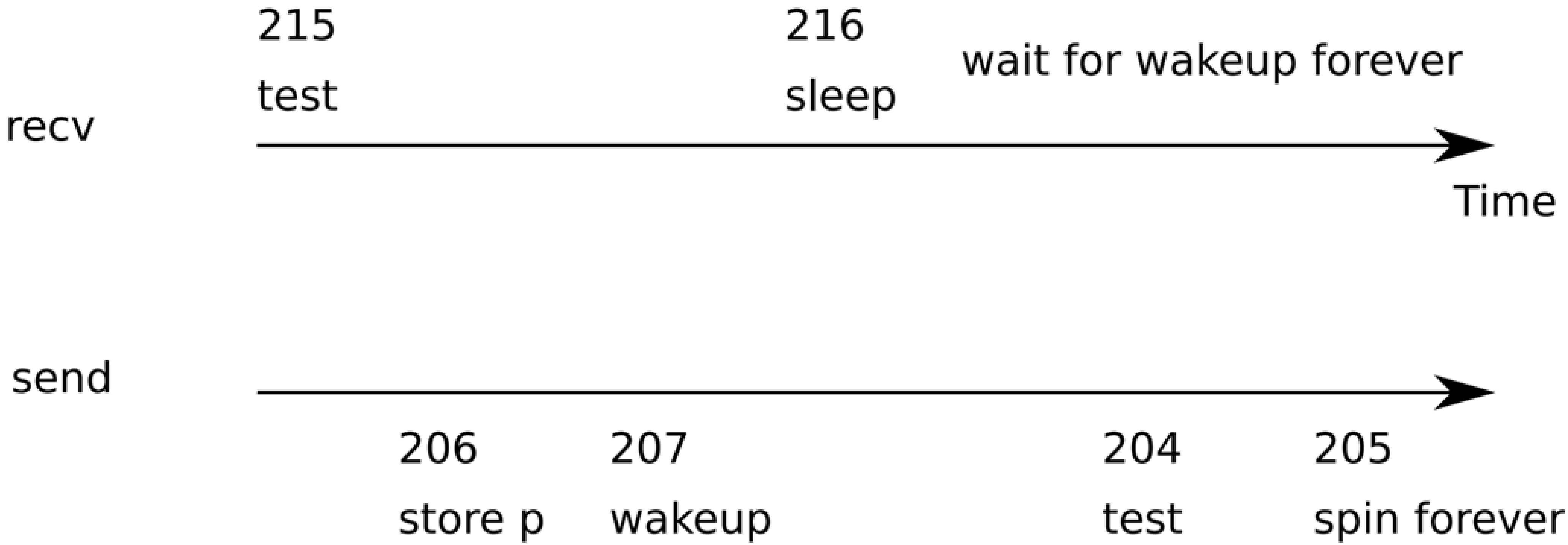
Send/receive queue

```
void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
  wakeup(q); /*wake recv*/
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    sleep(q);
  q->ptr = 0;
  return p;
}
```

- recv() gives up the CPU to other processes
- But there is a problem...

Lost wakeup problem



Lock the queue

```
struct q {
  struct spinlock lock;
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  acquire(&q->lock);
  while(q->ptr != 0)
    ;
  q->ptr = p;
  wakeup(q);
  release(&q->lock);
}
```

```
void*
recv(struct q *q)
{
  void *p;

  acquire(&q->lock);
  while((p = q->ptr) == 0)
    sleep(q);
  q->ptr = 0;
  release(&q->lock);
  return p;
}
```

- Doesn't work either: deadlocks
- Holds a lock while sleeping

Pass lock inside sleep()

```
struct q {
  struct spinlock lock;
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  acquire(&q->lock);
  while(q->ptr != 0)
    ;
  q->ptr = p;
  wakeup(q);
  release(&q->lock);
}
```

```
void*
recv(struct q *q)
{
  void *p;

  acquire(&q->lock);
  while((p = q->ptr) == 0)
    sleep(q, &q->lock);
  q->ptr = 0;
  release(&q->lock);
  return p;
}
```

sleep()

```
sleep(void *chan, struct spinlock *lk)
{
...
  if(lk != &ptable.lock){
    acquire(&ptable.lock);
    release(lk);
  }

  // Go to sleep.
  proc−>chan = chan;
  proc−>state = SLEEPING;
  sched();
...
  // Reacquire original lock.
  if(lk != &ptable.lock){
    release(&ptable.lock);
    acquire(lk);
  }
}
```

- Two steps:
- Acquire ptable.lock
  - All process operations are protected with ptable.lock

sleep()

```
sleep(void *chan, struct spinlock *lk)
{
...
  if(lk != &ptable.lock){
    acquire(&ptable.lock);
    release(lk);
  }

  // Go to sleep.
  proc−>chan = chan;
  proc−>state = SLEEPING;
  sched();
...
  // Reacquire original lock.
  if(lk != &ptable.lock){
    release(&ptable.lock);
    acquire(lk);
  }
}
```

- Two steps:
- Acquire ptable.lock
  - All process operations are protected with ptable.lock
- Release lk lock
  - Why is it safe?

sleep()

```
sleep(void *chan, struct spinlock *lk)
{
...
  if(lk != &ptable.lock){
    acquire(&ptable.lock);
    release(lk);
  }

  // Go to sleep.
  proc−>chan = chan;
  proc−>state = SLEEPING;
  sched();
...
  // Reacquire original lock.
  if(lk != &ptable.lock){
    release(&ptable.lock);
    acquire(lk);
  }
}
```

- Acquire ptable.lock
  - All process operations are protected with ptable.lock
- Release lk
  - Why is it safe?
- Even if new wakeup starts at this point, it cannot proceed
  - Sleep() holds ptable.lock

wakeup()

```
wakeup1(void *chan)
{
  struct proc *p;

  for(p = ptable.proc; p < &ptable.proc[NPROC]; p++)
    if(p->state == SLEEPING && p->chan == chan)
      p->state = RUNNABLE;
}
..
wakeup(void *chan)
{
  acquire(&ptable.lock);
  wakeup1(chan);
  release(&ptable.lock);
}
```

Pipes

Pipe

```
#define PIPESIZE 512

struct pipe {
  struct spinlock lock;
  char data[PIPESIZE];
  uint nread; // number of bytes read
  uint nwrite; // number of bytes written
  int readopen; // read fd is still open
  int writeopen; // write fd is still open
};
```

Pipe

```
#define PIPESIZE 512

struct pipe {
  struct spinlock lock;
  char data[PIPESIZE];
  uint nread; // number of bytes read
  uint nwrite; // number of bytes written
  int readopen; // read fd is still open
  int writeopen; // write fd is still open
};
```

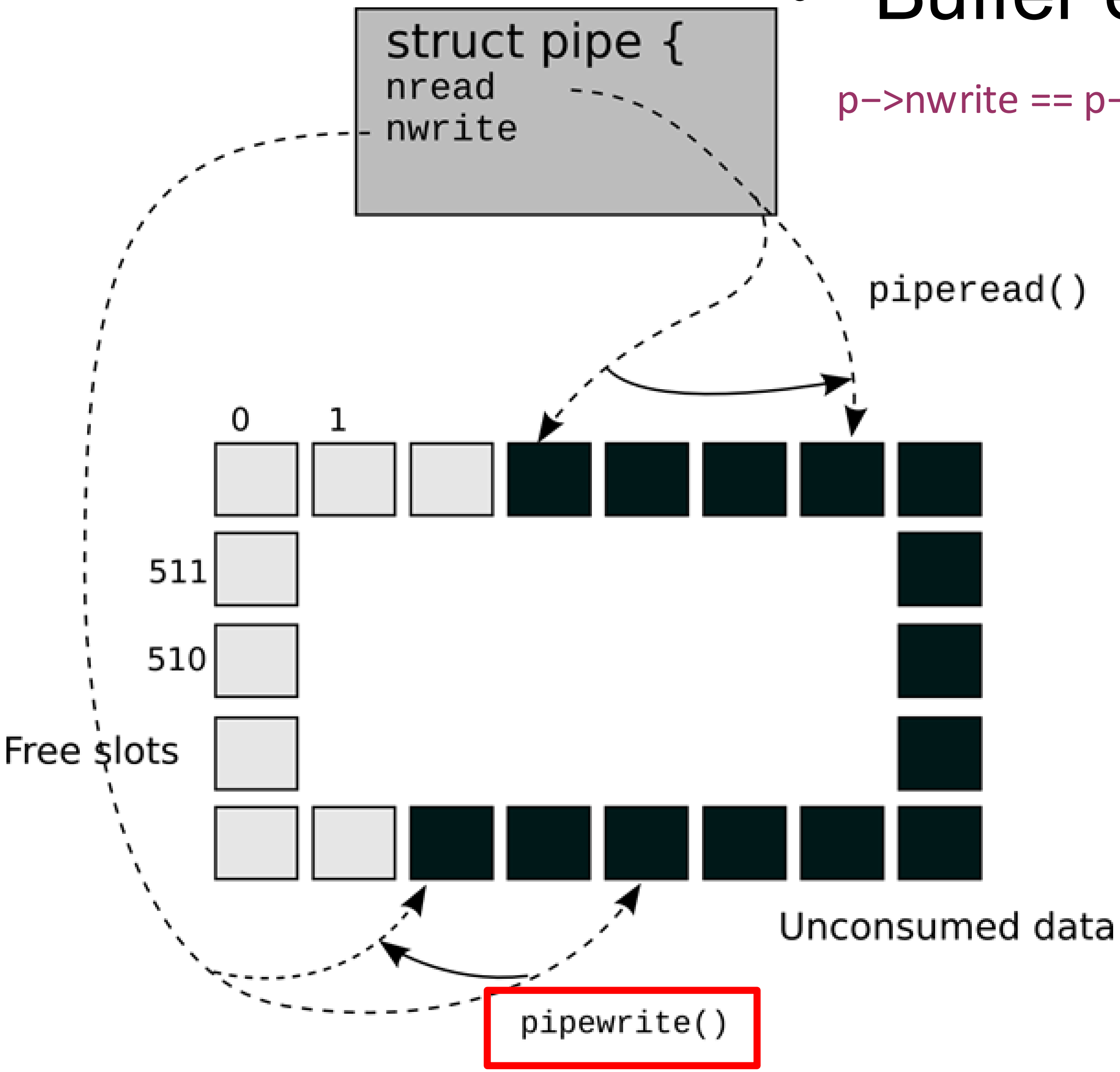
Pipe buffer

- Buffer full

p−>nwrite == p−>nread + PIPESIZE

- Buffer empty

p−>nwrite == p−>nread



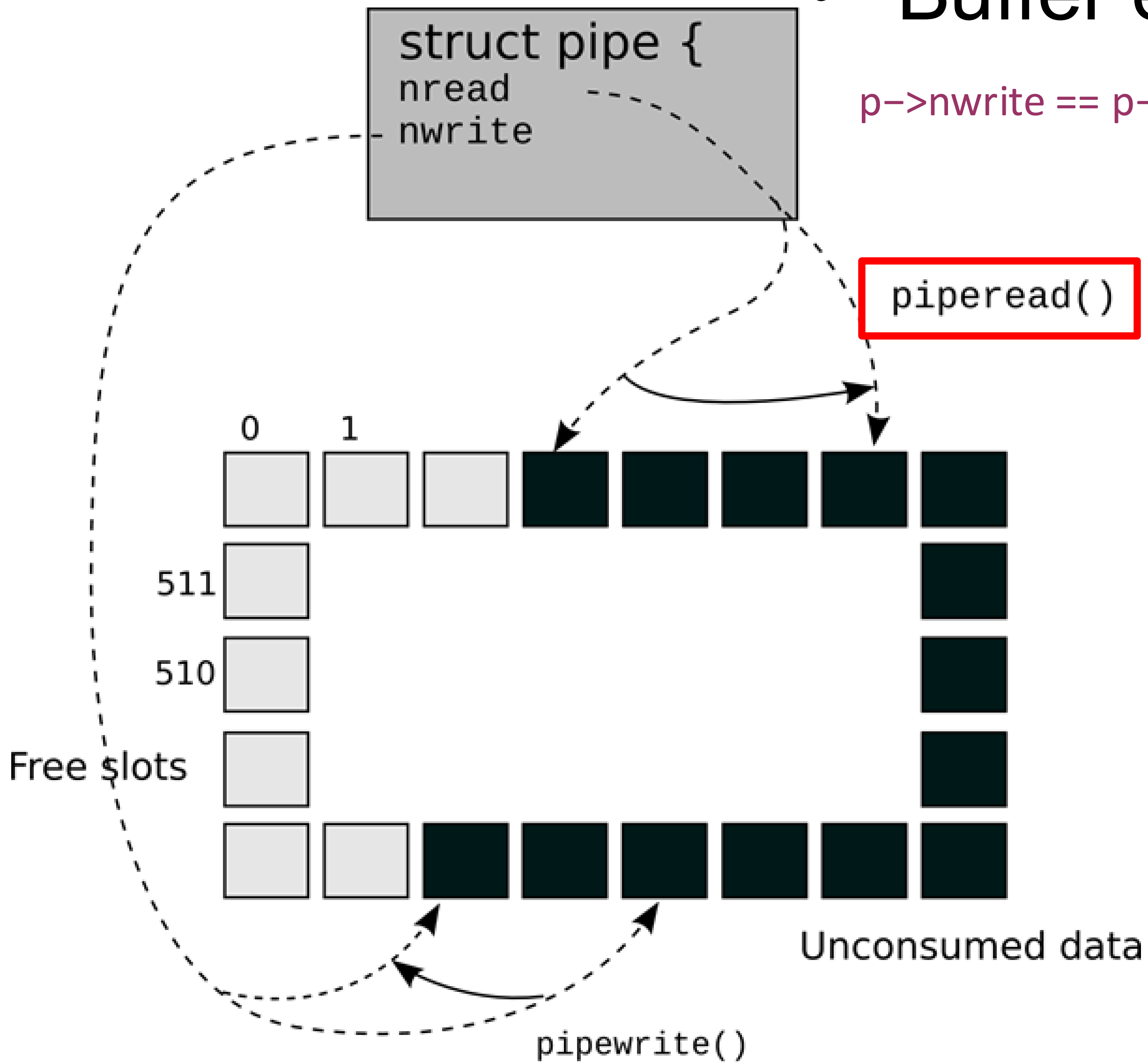
Pipe buffer

- Buffer full

  p−>nwrite == p−>nread + PIPESIZE

- Buffer empty

  p−>nwrite == p−>nread



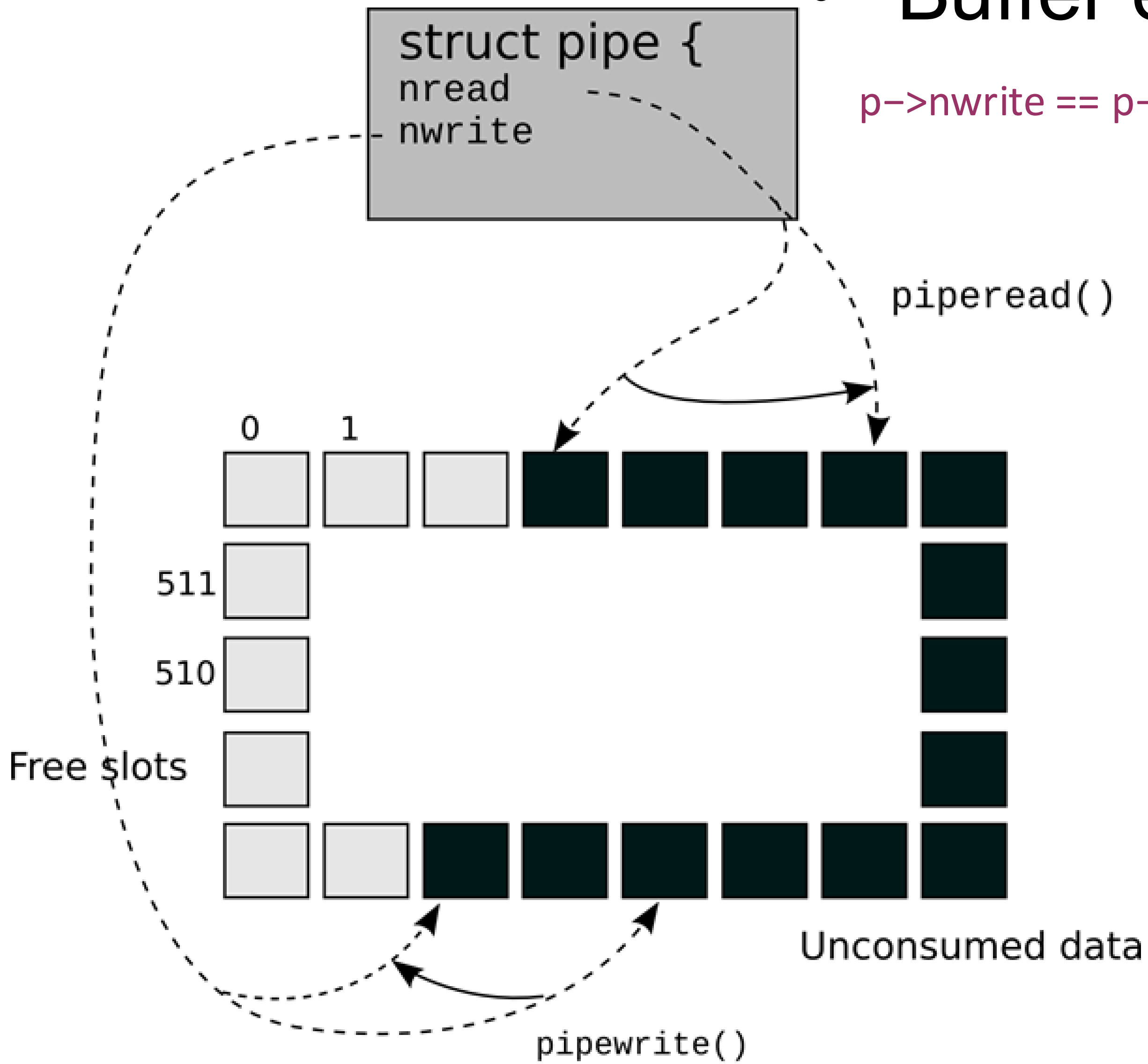
Pipe buffer

- Buffer full

p->nwrite == p->nread + PIPESIZE

- Buffer empty

p->nwrite == p->nread



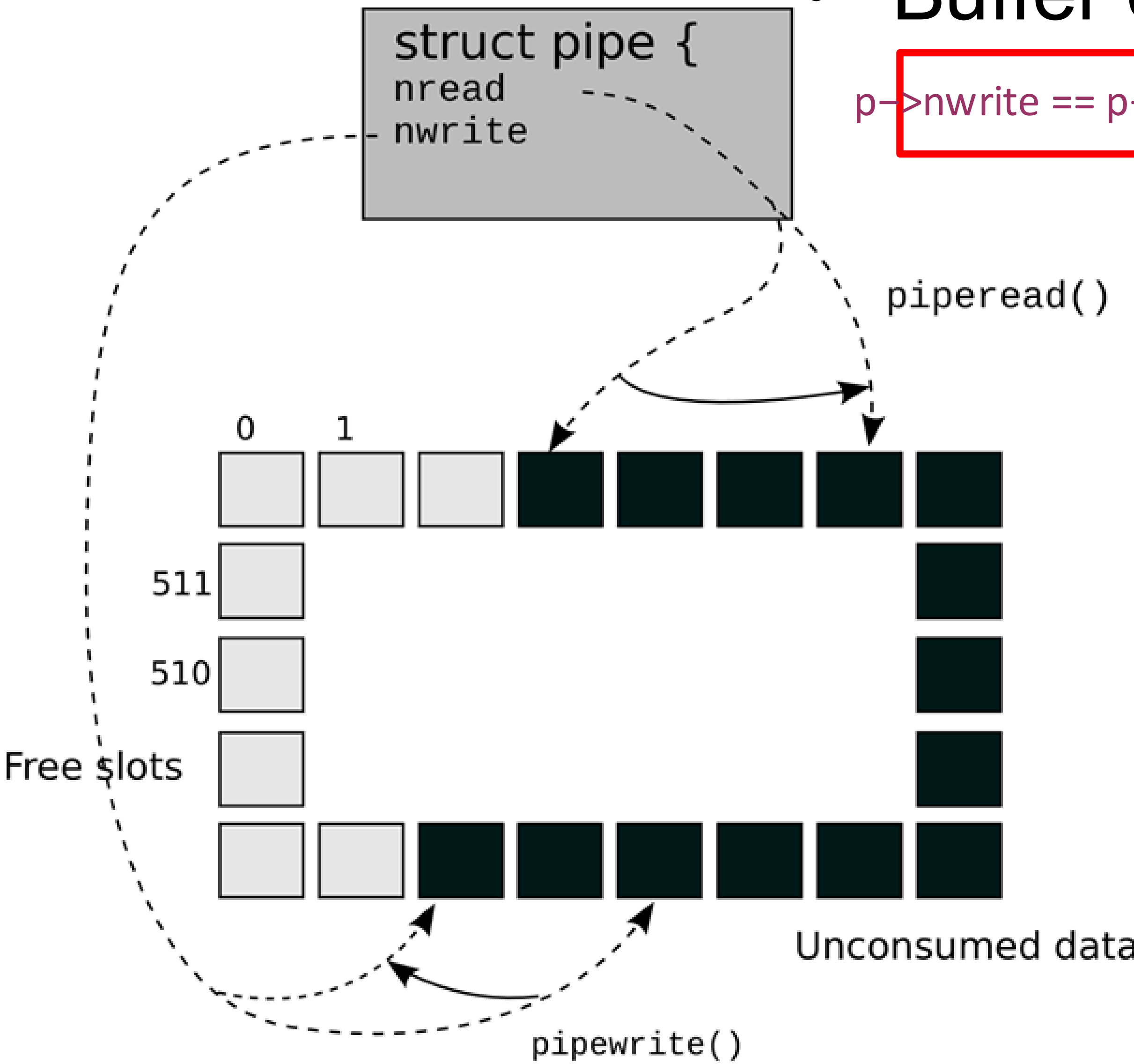
Pipe buffer

- Buffer full

p−>nwrite == p−>nread + PIPESIZE

- Buffer empty

p−>nwrite == p−>nread



piperead()

```
piperead(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p−>lock);
  while(p−>nread == p−>nwrite && p−>writeopen){
    if(proc−>killed){
      release(&p−>lock);
      return −1;
    }
    sleep(&p−>nread, &p−>lock);
  }
  ...
```

- Acquire pipe lock
- All pipe operations are are protected with the lock

piperead()

```
piperead(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  while(p->nread == p->nwrite && p->writeopen){
    if(proc->killed){
      release(&p->lock);
      return -1;
    }
    sleep(&p->nread, &p->lock);
  }
  ...
```

- If the buffer is empty && the write end is still open
- Go to sleep

piperead()

```
piperead(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  while(p->nread == p->nwrite && p->writeopen){
    if(proc->killed){
      release(&p->lock);
      return -1;
    }
    sleep(&p->nread, &p->lock);
  }
  for(i = 0; i < n; i++){
    if(p->nread == p->nwrite)
      break;
    addr[i] = p->data[p->nread++ % PIPESIZE];
  }
  wakeup(&p->nwrite);
  release(&p->lock);
  return i;
}
```

- After reading some data from the buffer
- Wakeup the writer

pipewrite()

- If the buffer is full
- Wakeup reader
- Go to sleep

```
pipewrite(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  for(i = 0; i < n; i++){
    while(p->nwrite == p->nread + PIPESIZE){
      if(p->readopen == 0 || proc->killed){
        release(&p->lock);
        return -1;
      }
      wakeup(&p->nread);
      sleep(&p->nwrite, &p->lock);
    }
    p->data[p->nwrite++ % PIPESIZE] = addr[i];
  }
  wakeup(&p->nread);
  release(&p->lock);
  return n;
}
```

pipewrite()

```
pipewrite(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p−>lock);
  for(i = 0; i < n; i++){
    while(p−>nwrite == p−>nread + PIPESIZE){
      if(p−>readopen == 0 || proc−>killed){
        release(&p−>lock);
        return −1;
      }
      wakeup(&p−>nread);
      sleep(&p−>nwrite, &p−>lock);
    }
    p−>data[p−>nwrite++ % PIPESIZE] = addr[i];
  }
  wakeup(&p−>nread);
  release(&p−>lock);
  return n;
}
```

- If the buffer is full
  - Wakeup reader
  - Go to sleep
- However, if the read end is closed
  - Return an error
  - (-1)

pipewrite()

```
pipewrite(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  for(i = 0; i < n; i++){
    while(p->nwrite == p->nread + PIPESIZE){
      if(p->readopen == 0 || proc->killed){
        release(&p->lock);
        return -1;
      }
      wakeup(&p->nread);
      sleep(&p->nwrite, &p->lock);
    }
    p->data[p->nwrite++ % PIPESIZE] = addr[i];
  }
  wakeup(&p->nread);
  release(&p->lock);
  return n;
}
```

- Otherwise keep writing bytes into the pipe
- When done
- Wakeup reader

Thank you!