CS3210: Multiprocessors and Locking

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Administrivia

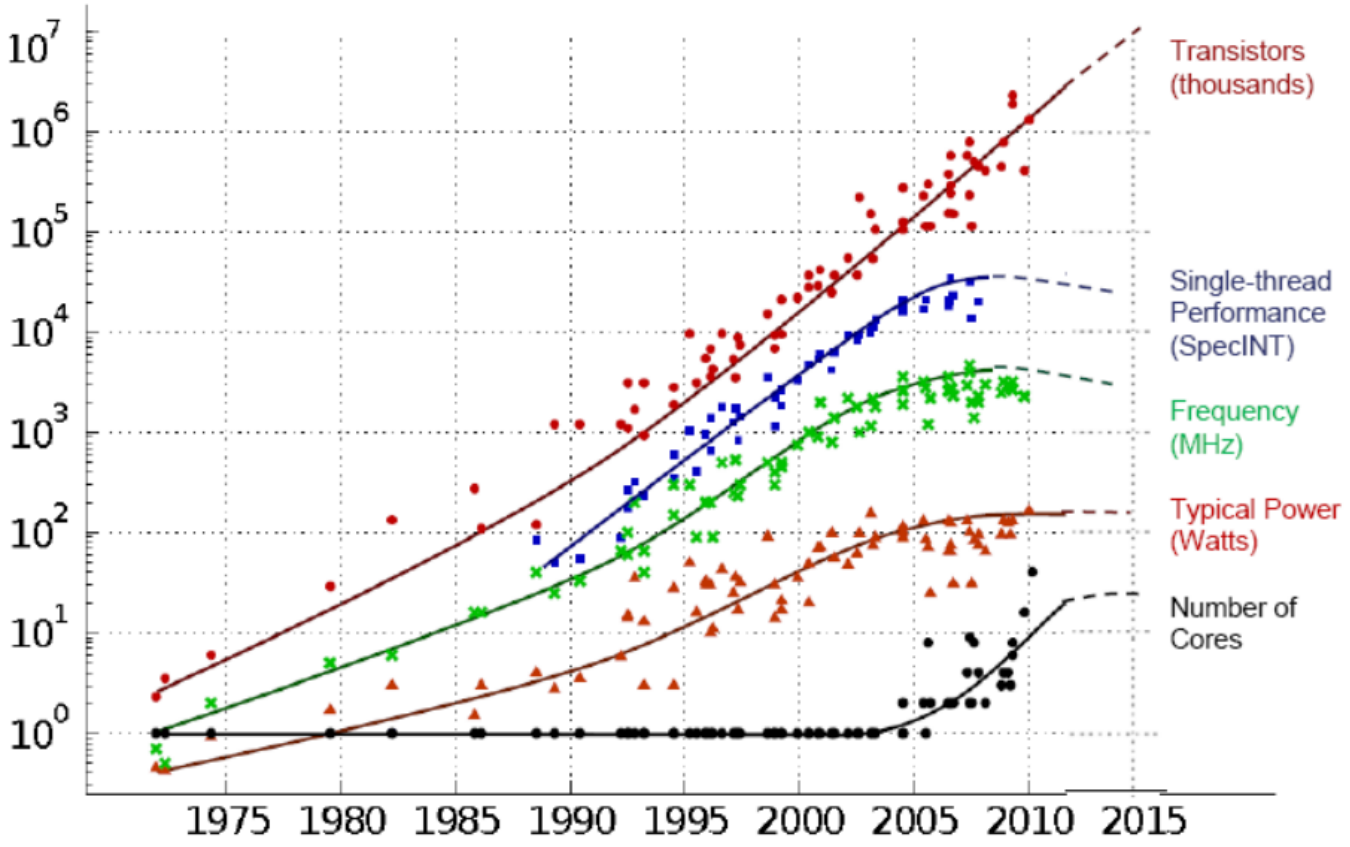
- Lab 3 (Part A), due Feb 24
- Lab 3 (Part B), due Mar 3
- Drop Date approaching (Mar 15)
- Team Proposal (3-5 min/team) - Mar 7

Summary of last lectures

- Power-on -> BIOS -> bootloader -> kernel -> init (+ user bins)
- OS: abstraction, multiplexing, isolation, sharing
- Design: monolithic (xv6) vs. micro kernels (jos)
- Abstraction: process, system calls
- Isolation mechanisms: CPL, segmentation, paging
- Interrupts, exceptions

Today: Multiprocessor (and locking?)

Motivation:



Original data collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Batten
Dotted line extrapolations by C. Moore

Further motivation: Lab 4

- Multiple CPUs running kernel code can cause race conditions
- We will approach this problem by implementing (utilizing) locks in the proper locations
- Let us further understand the implementation challenges and tradeoffs with locks (very much always an open research area and performance concern)

Preparation Question

```
int count = 0;

void* run(void *arg)
{
  register int cnt = *(int *)arg;
  for (register int i = 0; i < cnt; i++) {
    asm volatile("incl %0"
                 : "+m"(count)
                 : "m"(count)
                 : "memory");
  }
  return NULL;
}
```

Preparation Question

```c
int main(int argc, char *argv[])
{
  int ncpu = atoi(argv[1]);
  int upto = atoi(argv[2]);

  pthread_t *tids = malloc(ncpu * sizeof(pthread_t));

  for (int i = 0; i < ncpu ; i ++) {
    if (pthread_create(&tids[i], NULL, run, &upto))
      err(1, "failed to creat a thread");
  }
  for (int i = 0; i < ncpu ; i ++)
    pthread_join(tids[i], NULL);

  printf("cpu = %d, count = %d\n", ncpu, count);

  return 0;
}
```

Example: counting

- DEMO: `count.c`

```
$ ./count 1 10
cpu = 1, count = 10

$ ./count 2 5
cpu = 2, count = 10

$ ./count 1 10000
cpu = 1, count = 10000

$ ./count 2 5000
cpu = 2, count = 10000

$ ./count 1 100000
cpu = 1, count = 100000

$ ./count 2 50000
cpu = 2, count = 53494
```

Example: Measuring Execution Time

- Execution time reduces by half (x2 utilization)
- Q: problem?

```
$ time ./count 1 1000000000
cpu = 1, count = 1000000000
./count 1 1000000000  2.25s user 0.00s system 99% cpu 2.258 total

$ time ./count 2  500000000
cpu = 2, count = 502495507
./count 2  500000000  2.31s user 0.00s system 197% cpu 1.165 total
```

Example: analysis in detail

```
$ perf stat ./count 1 1000000000
cpu = 1, count = 1000000000

 Performance counter stats for './count 1 1000000000':

       2251.705855      task-clock (msec)         #    0.999 CPUs utilized
               88      context-switches          #    0.039 K/sec
                3      cpu-migrations            #    0.001 K/sec
               56      page-faults               #    0.025 K/sec
    7,135,385,783      cycles                    #    3.169 GHz
   <not supported>     stalled-cycles-frontend
   <not supported>     stalled-cycles-backend
    4,005,413,202      instructions              #    0.56  insns per cycle
    1,000,979,696      branches                  #  444.543 M/sec
           17,505      branch-misses             #    0.00% of all branches

       2.252871308 seconds time elapsed
```

Example: analysis in detail

```
$ perf stat ./count 2  500000000
cpu = 2, count = 503059602

 Performance counter stats for './count 2  500000000':

       2349.797354      task-clock (msec)         #    1.992 CPUs utilized
                19      context-switches          #    0.008 K/sec
                 4      cpu-migrations            #    0.002 K/sec
                58      page-faults               #    0.025 K/sec
     7,274,653,523      cycles                    #    3.096 GHz
   <not supported>      stalled-cycles-frontend
   <not supported>      stalled-cycles-backend
     4,003,964,870      instructions              #    0.55  insns per cycle
     1,000,732,490      branches                  #  425.880 M/sec
            19,942      branch-misses             #    0.00% of all branches

       1.179731295 seconds time elapsed
```

Q: How to fix this problem?

- Two (competing?) goals:
  - **Correctness**: no missing counts
  - **Performance**: execution time

Attempt 1: use only one CPU

- `pin_cpu(0)`: fix its execution to the first CPU (id = 0)

```
01  void pin_cpu(int cpu) {
02    cpu_set_t cpuset;
03    CPU_ZERO(&cpuset);
04    CPU_SET(cpu, &cpuset);
05
06    if (pthread_setaffinity_np(pthread_self(), \
07                               sizeof(cpu_set_t), &cpuset) < 0)
08      err(1, "failed to set affinity");
09  }
```

Result (attempt 1)

- Q: correctness? performance?

```
$ time ./count 1 1000000000
cpu = 1, count = 1000000000
2.26s user 0.00s system 99% cpu 2.266 total

$ time ./count 2  500000000
cpu = 2, count = 1000000000
2.31s user 0.00s system 99% cpu 2.316 total
```

Attempt 2: use atomic operation

- Add a lock prefix (all memory ops)

```
01    asm volatile("lock incl %0"
02                 : "+m"(count)
03                 : "m"(count)
04                 : "memory");
```

Result

- Q: correctness? performance?

```
$ time ./count 1 1000000000
cpu = 1, count = 1000000000
6.64s user 0.00s system 99% cpu 6.644 total

$ time ./count 2  500000000
cpu = 2, count = 1000000000
49.76s user 0.00s system 199% cpu 24.893 total
```

Analysis (see stall cycles)

```
$ perf stat ./count 2  500000000
cpu = 2, count = 1000000000

 Performance counter stats for './count 2  500000000':

   62475.069100      task-clock (msec)         #    1.988 CPUs utilized
          5,228      context-switches          #    0.084 K/sec
              3      cpu-migrations            #    0.000 K/sec
             80      page-faults               #    0.001 K/sec
134,913,649,220      cycles                    #    2.159 GHz
133,127,752,850      stalled-cycles-frontend   #   98.68% frontend cycles idle
 78,451,841,095      stalled-cycles-backend    #   58.15% backend  cycles idle
  4,103,848,320      instructions              #    0.03  insns per cycle
                                               #   32.44  stalled cycles per insn
  1,018,681,684      branches                  #   16.305 M/sec
        474,657      branch-misses             #    0.05% of all branches

    31.427313911 seconds time elapsed
```

Attempt 3: compute locally (per CPU)

- Q: correctness? performance?
- Q: how to improve perf even further?
- Q: how to trigger a race?

```
01    int local = 0;
02    for (register int i = 0; i < cnt; i++)
03      local ++;
04
05    count += local;
```

Attempt 3: compute locally (per CPU)

- Q: correctness? performance?
- Q: how to improve perf even further?
- Q: how to trigger a race?

```
01    int local = 0;
02    for (register int i = 0; i < cnt; i++)
03      local ++;
04
05    count += local;
```

```
$ time ./count_local 1 1000000000
cpu = 1, count = 1000000000
real    0m1.847s
user    0m1.832s
sys     0m0.012s

$ time ./count_local 2 500000000
cpu = 2, count = 1000000000

real    0m0.896s
user    0m1.780s
sys     0m0.004s
```

Attempt 4: using locks

```
01    int local = 0;
02    for (register int i = 0; i < cnt; i++)
03      local ++;
04
05    acquire(&lock);
06    count += local;
07    release(&lock)
```

Attempt 4: using locks

```
01    int local = 0;
02    for (register int i = 0; i < cnt; i++)
03      local ++;
04
05    acquire(&lock);
06    count += local;
07    release(&lock)
```

- Perhaps a reasonable solution
  - Lock is localized to where we need it (contention low)
  - Performance is good
  - Correctness is good

Locks

- **Mutual exclusion**: only one core can hold a given lock
  - concurrent access to the same memory location, at least one write
  - example: `acquire(l); x = x + 1; release(l);`
- **Serialize** critical section: hide intermediate state
  - another example: transfer money from account A to B
  - `put(a + 100)` and `put(b - 100)` must be both effective, or neither

Strawman: locking

```
01    struct lock { int locked; };
02
03    void acquire(struct lock *l) {
04      for (;;) {
05        if (l->locked == 0) { // A: test
06          l->locked = 1;      // B: set
07          return;
08        }
09      }
10    }
11
12    void release(struct lock *l) {
13      l->locked = 0;
14    }
```

Strawman: locking

```
01    struct lock { int locked; };
02
03    void acquire(struct lock *l) {
04      for (;;) {
05        if (l->locked == 0) { // A: test
06          l->locked = 1;      // B: set
07          return;
08        }
09      }
10    }
11
12    void release(struct lock *l) {
13      l->locked = 0;
14    }
```

- No, this doesn't work
- Non-atomic test and set has a race condition

Relying on an atomic operation

- Q: correctness? performance?

```
01    struct lock { int locked; };
02
03    void acquire(struct lock *l) {
04      for (;;) {
05        if (xchg(&l->locked, 1) == 0)
06          return;
07      }
08    }
09
10    void release(struct lock *l) {
11      xchg(&l->locked, 0);
12    }
```

Using xchg: an atomic operation (primitive)

- `x86.h` in xv6

```
01    int xchg(volatile int *addr, int newval) {
02      int result;
03      // The + in "+m" denotes a read-modify-write operand.
04      asm volatile("lock; xchgl %0, %1" :
05                   "+m" (*addr), "=a" (result) :
06                   "1" (newval) :
07                   "cc");
08      return result;
09    }
```

Result

```
$ time ./count_xchg 1 1000000000
cpu = 1, count = 1000000000

real    0m1.876s
user    0m1.872s
sys     0m0.012s

$ time ./count_xchg 2 500000000
cpu = 2, count = 1000000000

real    0m0.925s
user    0m1.832s
sys     0m0.008s
```

Attempt 5: lockless? add (atomically)

- Q: correctness? performance?

```
asm volatile("mov %1, %%eax\n\t"
             "lock add %%eax, %0\n\t"
             : "+m"(count)
             : "m"(local), "m"(count)
             : "memory");
```

```
__atomic_add_fetch(&count, local, __ATOMIC_RELEASE);
```

Attempt 5: lockless? add (atomically)

- Q: correctness? performance?

```
  asm volatile("mov %1, %%eax\n\t"
               "lock add %%eax, %0\n\t"
               : "+m"(count)
               : "m"(local), "m"(count)
               : "memory");
```

```
  __atomic_add_fetch(&count, local, __ATOMIC_RELEASE);
```

```
$ time ./count_atomicadd 1 1000000000
cpu = 1, count = 0

real    0m5.035s
user    0m5.008s
sys     0m0.016s
```

Spinlock in xv6

- Pretty much same, but provide debugging info

```
01  struct spinlock {
02    uint locked;       // Is the lock held?
03
04    // Q?
05    char *name;        // Name of lock.
06    struct cpu *cpu;   // The cpu holding the lock.
07    uint pcs[10];      // The call stack (an array of program counters)
08                       // that locked the lock.
09  };
```

`acquire()` in xv6

```
01  void acquire(struct spinlock *lk) {
02    pushcli(); // disable interrupts to avoid deadlock.
03    if (holding(lk))
04      panic("acquire");
05
06    // The xchg is atomic.
07    // It also serializes, so that reads after acquire are not
08    // reordered before it.
09    while (xchg(&lk->locked, 1) != 0)
10      ;
11
12    // Record info about lock acquisition for debugging.
13    lk->cpu = cpu;
14    getcallerpcs(&lk, lk->pcs);
15  }
```

`release()` in xv6

```
01  void release(struct spinlock *lk) {
02    if (!holding(lk))
03      panic("release");
04
05    lk=>pcs[0] = 0;
06    lk=>cpu = 0;
07
08    // Q?
09    xchg(&lk=>locked, 0);
10
11    popcli();
12  }
```

References

- Intel Manual
- UW CSE 451
- OSPP
- MIT 6.828
- Wikipedia
- The Internet