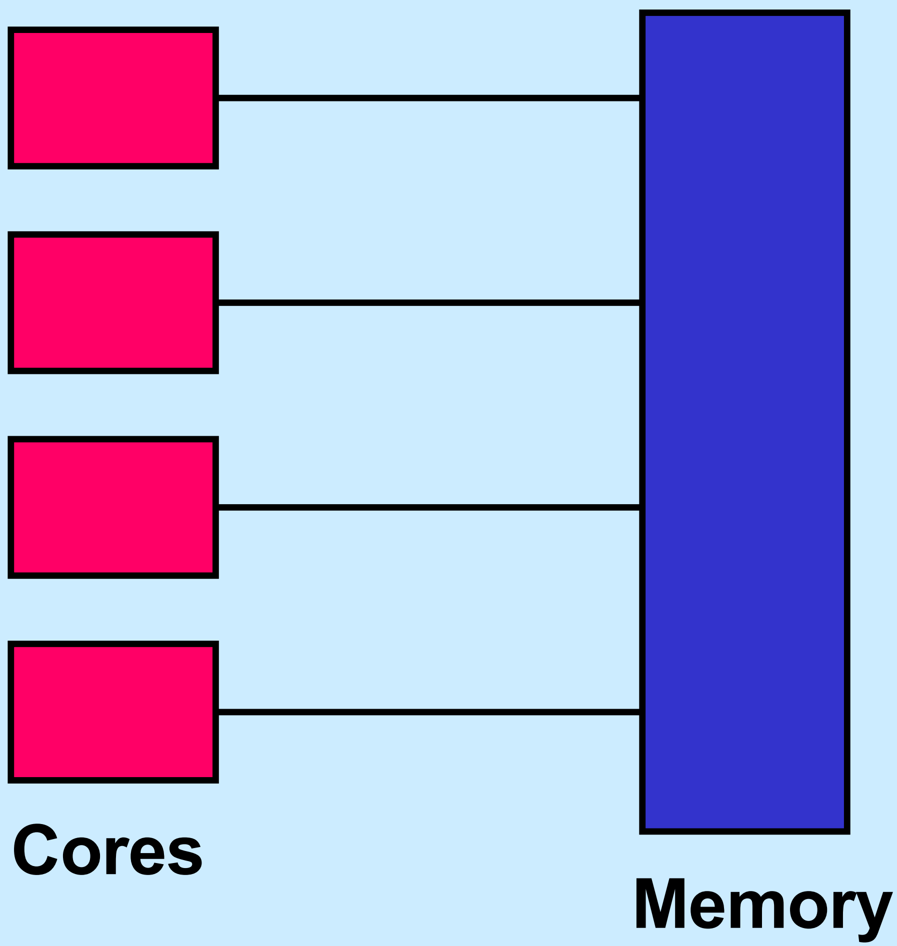
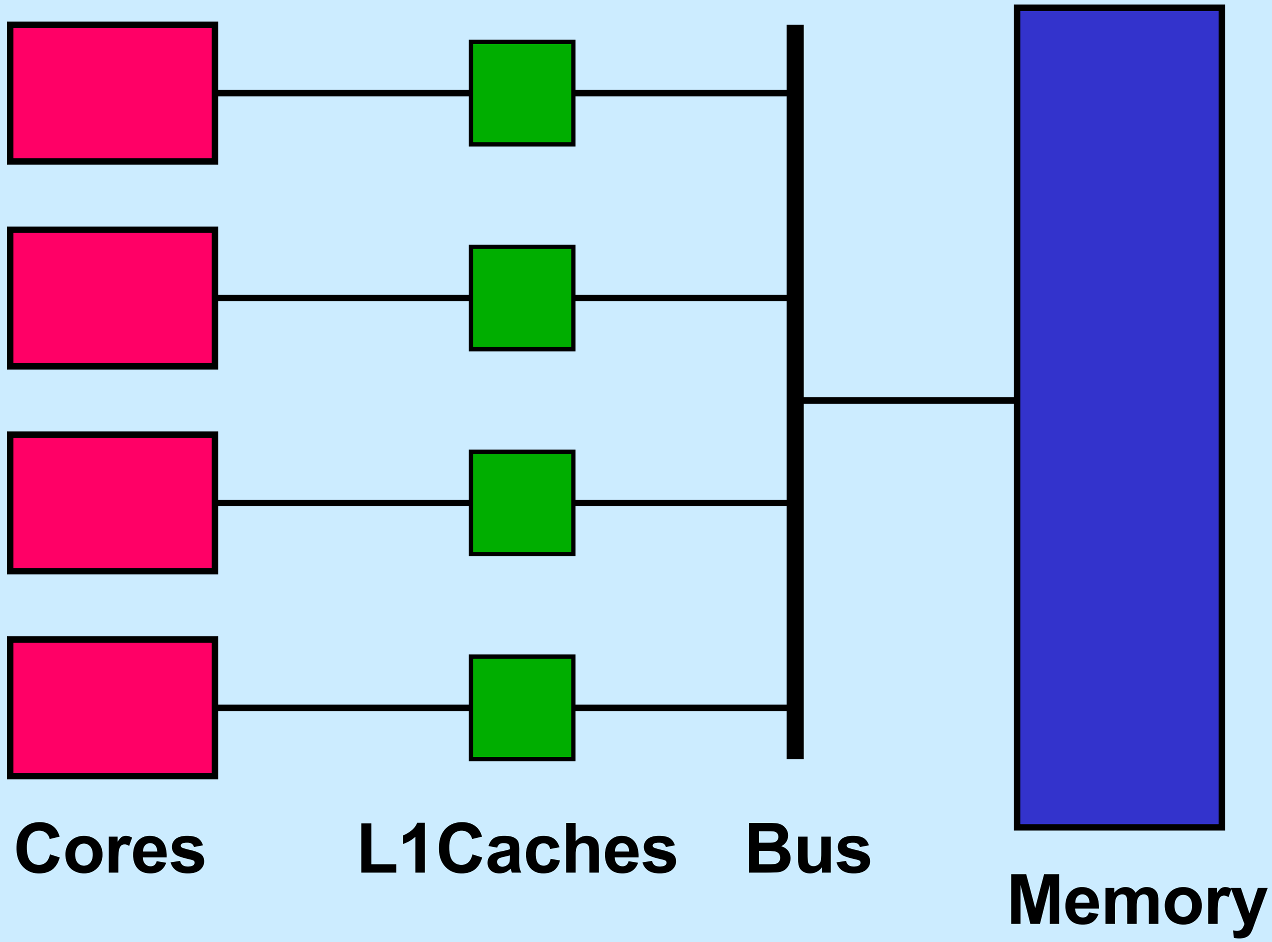
CS 33

Multithreaded Programming VI

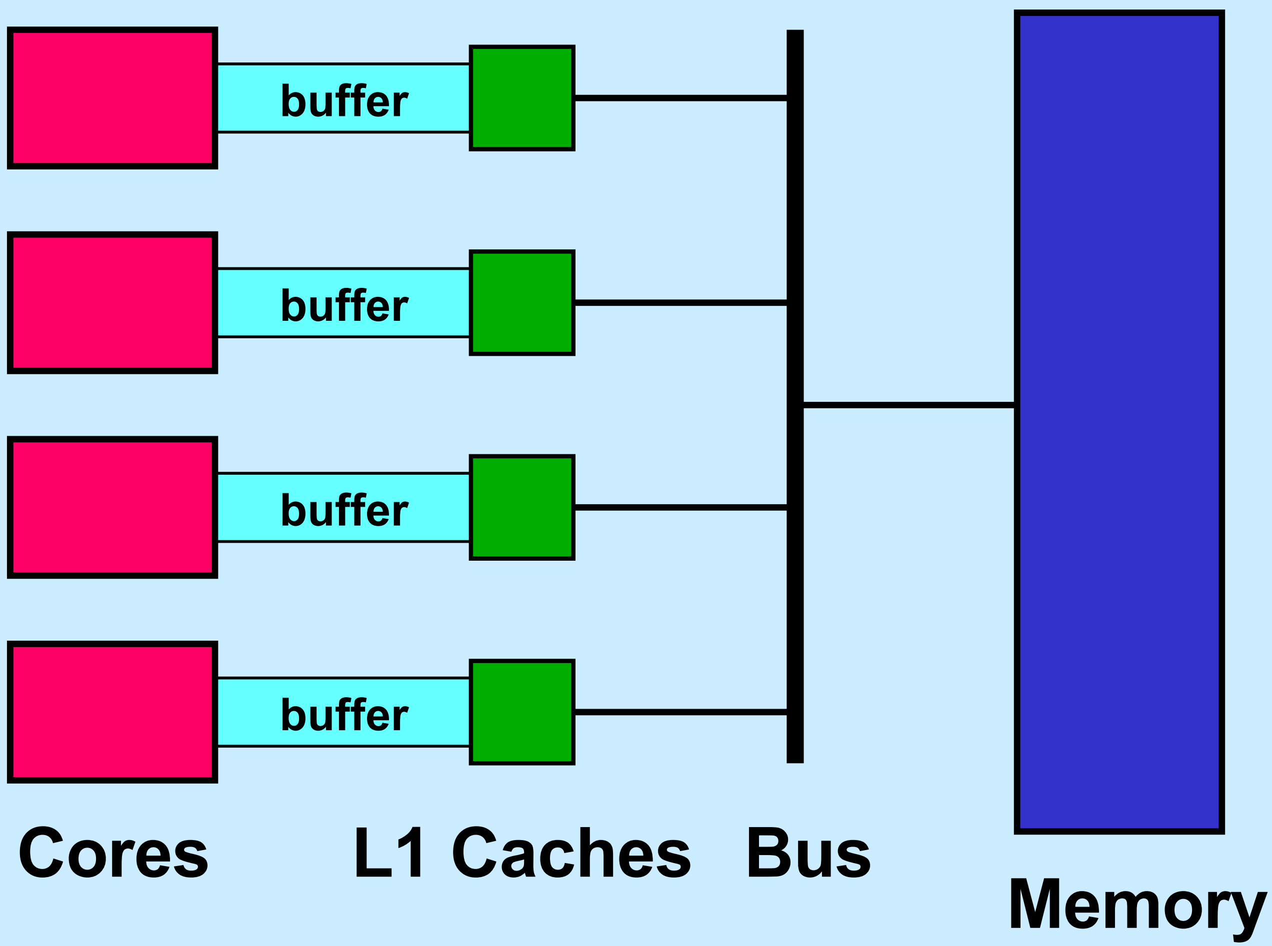
Multi-Core Processor: Simple View



Multi-Core Processor: More Realistic View



Multi-Core Processor: Even More Realistic



Concurrent Reading and Writing

Thread 1:

```
i = shared_counter;
```

Thread 2:

```
shared_counter++;
```

Mutual Exclusion w/o Mutexes

```
void peterson(long me) {
  static long loser;                    // shared
  static long active[2] = {0, 0};       // shared
  long other = 1 - me;                  // private
  active[me] = 1;
  loser = me;
  while (loser == me && active[other])
    ;
  // critical section
  active[me] = 0;
}
```


Busy-Waiting Producer/Consumer

```
void producer(char item) {

  while(in - out == BSIZE)
    ;

  buf[in%BSIZE] = item;

  in++;
}
```

```
char consumer( ) {
  char item;
  while(in - out == 0)
    ;

  item = buf[out%BSIZE];

  out++;

  return(item);
}
```

Quiz 1

```
void producer(char item) {

  while(in - out == BSIZE)
   ;

  buf[in%BSIZE] = item;

  in++;
}
```

```
char consumer( ) {
  char item;
  while(in - out == 0)
   ;

  item = buf[out%BSIZE];

  out++;

  return(item);
}
```

This works on sunlab machines.

a) true
b) false

Coping

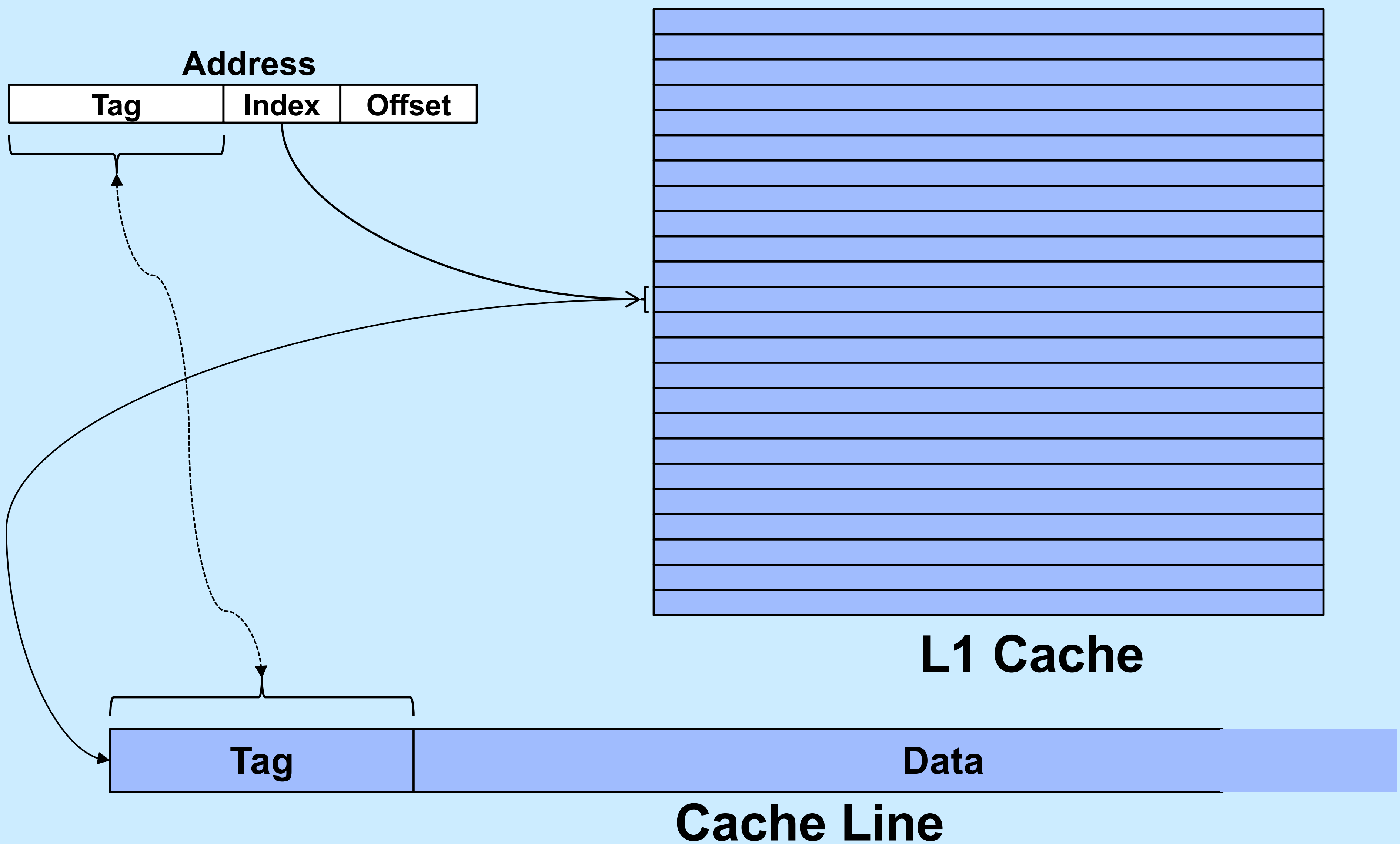
- Don’t rely on shared memory for synchronization
- Use the synchronization primitives

Which Runs Faster?

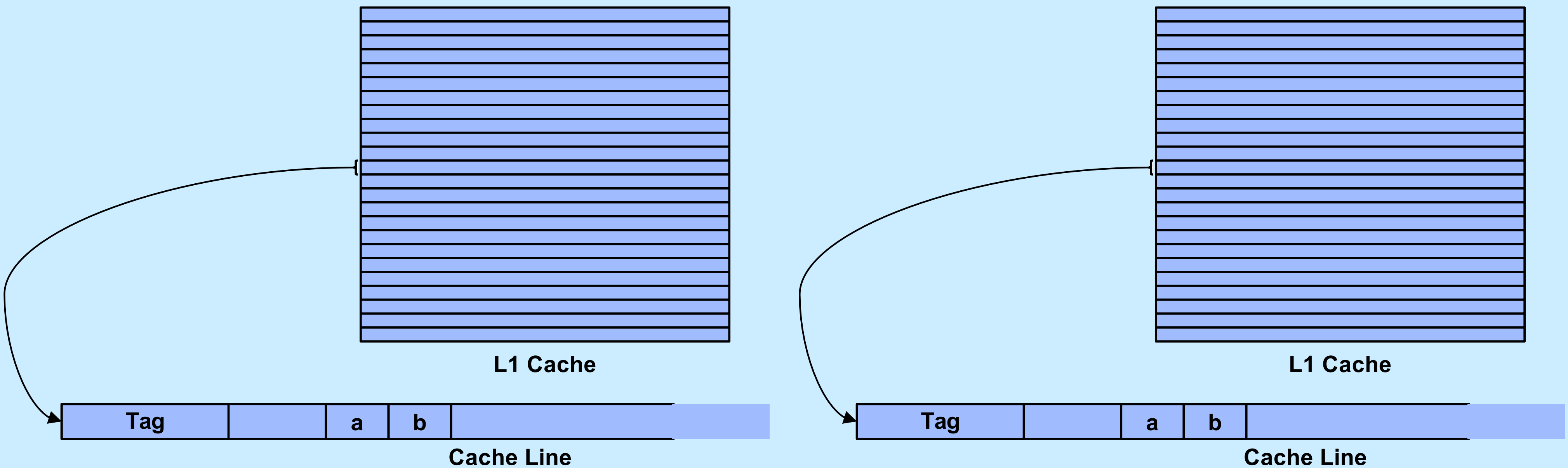
```
volatile int a, b;

void *thread1(void *arg) {
  int i;
  for (i=0; i<reps; i++) {
    a = 1;
  }
}

void *thread2(void *arg) {
  int i;
  for (i=0; i<reps; i++) {
    b = 1;
  }
}
```

```
volatile int a,
  padding[128], b;

void *thread1(void *arg) {
  int i;
  for (i=0; i<reps; i++) {
    a = 1;
  }
}

void *thread2(void *arg) {
  int i;
  for (i=0; i<reps; i++) {
    b = 1;
  }
}
```

Cache Lines



False Sharing



Implementing Mutexes

- **Strategy**
  - make the usual case (no waiting) very fast
  - can afford to take more time for the other case (waiting for the mutex)

Futexes

- Safe, *efficient* kernel conditional queueing in Linux
- All operations performed atomically
  - `futex_wait(futex_t *futex, int val)`
    - » if `futex->val` is equal to `val`, then sleep
    - » otherwise return
  - `futex_wake(futex_t *futex)`
    - » wake up one thread from `futex`'s wait queue, if there are any waiting threads

Ancillary Functions

- **int** `atomic_inc(`**int** `*val)`
  - **add 1 to `*val`, return its original value**
- **int** `atomic_dec(`**int** `*val)`
  - **subtract 1 from `*val`, return its original value**
- `int CAS(int *ptr, int old, int new) {`

```
      int tmp = *ptr;
      if (*ptr == old)
         *ptr = new;
      return tmp;
  }
```

Attempt 1

```
void lock(futex_t *futex) {
  int c;
  while ((c = atomic_inc(&futex->val)) != 0)
    futex_wait(futex, c+1);
}

void unlock(futex_t *futex) {
  futex->val = 0;
  futex_wake(futex);
}
```


Attempt 2

```
void lock(futex_t *futex) {
  int c;
  if ((c = CAS(&futex->val, 0, 1) != 0)
    do {
      if (c == 2 || (CAS(&futex->val, 1, 2) != 0))
        futex_wait(futex, 2);
    while ((c = CAS(&futex->val, 0, 2)) != 0))
}

void unlock(futex_t *futex) {
  if (atomic_dec(&futex->val) != 1) {
    futex->val = 0;
    futex_wake(futex);
  }
}
```


Memory Allocation

- Multiple threads
- One heap

Bottleneck?

Solution 1

- Divvy up the heap among the threads
  – each thread has its own heap
  – no mutexes required
  – no bottleneck
- How much heap does each thread get?

Solution 2

- Multiple "arenas"
  – each with its own mutex
  – thread allocates from the first one it can find whose mutex was unlocked
    » if none, then creates new one
  – deallocations go back to original arena

Solution 3

- Global heap plus per-thread heaps
  - threads pull storage from global heap
  - freed storage goes to per-thread heap
    - » unless things are imbalanced
      - then thread moves storage back to global heap
  - mutex on only the global heap
- What if one thread allocates and another frees storage?

Malloc/Free Implementations

- **ptmalloc**
  - based on solution 2
  - in glibc (i.e., used by default)
- **tcmalloc**
  - based on solution 3
  - from Google
- **Which is best?**

Test Program

```
const unsigned int N=64, nthreads=32, iters=10000000;
int main() {
  void *tfunc(void *);
  pthread_t thread[nthreads];
  for (int i=0; i<nthreads; i++) {
    pthread_create(&thread[i], 0, tfunc, (void *)i);
    pthread_detach(thread[i]);
  }
  pthread_exit(0);
}
void *tfunc(void *arg) {
  long i;
  for (i=0; i<iters; i++) {
    long *p = (long *)malloc(sizeof(long)*((i%N)+1));
    free(p);
  }
  return 0;
}
```


Compiling It …

```
% gcc -o ptalloc alloc.cc -lpthread
% gcc -o tcalloc alloc.cc -lpthread -ltcmalloc
```


Running It (2014) …

```
$ time ./ptalloc
real    0m5.142s
user    0m20.501s
sys     0m0.024s
$ time ./tcalloc
real    0m1.889s
user    0m7.492s
sys     0m0.008s
```

What's Going On?

```
$ strace -c -f ./ptalloc
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
100.00    0.040002          13      3007       520 futex
 …


$ strace -c -f ./tcalloc
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 …
  0.00    0.000000           0        59        13 futex
 …
```


Test Program 2, part 1

```
#define N 64
#define npairs 16
#define allocsPerIter 1024
const long iters = 8*1024*1024/allocsPerIter;
#define BufSize 10240
typedef struct buffer {
  int *buf[BufSize];
  unsigned int nextin;
  unsigned int nextout;
  sem_t empty;
  sem_t occupied;
  pthread_t pthread;
  pthread_t cthread;
} buffer_t;
```

Test Program 2, part 2

```
int main() {
  long i;
  buffer_t b[npairs];
  for (i=0; i<npairs; i++) {
    b[i].nextin = 0;
    b[i].nextout = 0;
    sem_init(&b[i].empty, 0, BufSize/allocsPerIter);
    sem_init(&b[i].occupied, 0, 0);
    pthread_create(&b[i].pthread, 0, prod, &b[i]);
    pthread_create(&b[i].cthread, 0, cons, &b[i]);
  }
  for (i=0; i<npairs; i++) {
    pthread_join(b[i].pthread, 0);
    pthread_join(b[i].cthread, 0);
  }
  return 0;
}
```


Test Program 2, part 3

```
void *prod(void *arg) {
  long i, j;
  buffer_t *b = (buffer_t *)arg;
  for (i = 0; i<iters; i++) {
    sem_wait(&b->empty);
    for (j = 0; j<allocsPerIter; j++) {
      b->buf[b->nextin] = malloc(sizeof(int)*((j%N)+1));
      if (++b->nextin >= BufSize)
        b->nextin = 0;
    }
    sem_post(&b->occupied);
  }
  return 0;
}
```


Test Program 2, part 4

```
void *cons(void *arg) {
  long i, j;
  buffer_t *b = (buffer_t *)arg;
  for (i = 0; i<iters; i++) {
    sem_wait(&b->occupied);
    for (j = 0; j<allocsPerIter; j++) {
      free(b->buf[b->nextout]);
      if (++b->nextout >= BufSize)
        b->nextout = 0;
    }
    sem_post(&b->empty);
  }
  return 0;
}
```

Running It (2014) …

```
$ time ./ptalloc2
real     0m1.087s
user     0m3.744s
sys      0m0.204s
$ time ./tcalloc2
real     0m3.535s
user     0m11.361s
sys      0m2.112s
```

What's Going On?

```
$ strace -c -f ./ptalloc2
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 94.96    2.347314          44     53653     14030 futex
…
$ strace -c -f ./tcalloc2
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 93.86    6.604632          36    185731     45222 futex
 …
```

Running it (2015) ...

```
sphere $ time ./ptalloc

real    0m2.373s
user    0m9.152s
sys     0m0.008s
sphere $ time ./tcalloc

real    0m4.868s
user    0m19.444s
sys     0m0.020s
```

Running it (2015) ...

```
kui $ time ./ptalloc

real    0m2.787s
user    0m11.045s
sys     0m0.004s

kui $ time ./tcalloc

real    0m1.701s
user    0m6.584s
sys     0m0.004s
```


Running it (2015) ...

```
cslab0a $ time ./ptalloc

real    0m2.234s
user    0m8.468s
sys     0m0.000s

cslab0a $ time ./tcalloc

real    0m4.938s
user    0m19.584s
sys     0m0.000s
```

What's Going On?

- **On kui:**
  - `libtcmalloc.so -> libtcmalloc.so.4.1.0`
- **On other machines:**
  - `libtcmalloc.so -> libtcmalloc.so.4.2.2`

However (2015) ...

```
cslab0a $ time ./ptalloc2

real    0m0.466s
user    0m1.504s
sys     0m0.212s

cslab0a $ time ./tcalloc2

real    0m1.516s
user    0m5.212s
sys     0m0.328s
```

It’s 2020

- tcmalloc no longer exists
  - no explanation from Google, it’s simply gone
- ptmalloc continues to improve

