Introduction to Parallel Computing

Shared-memory systems and programming

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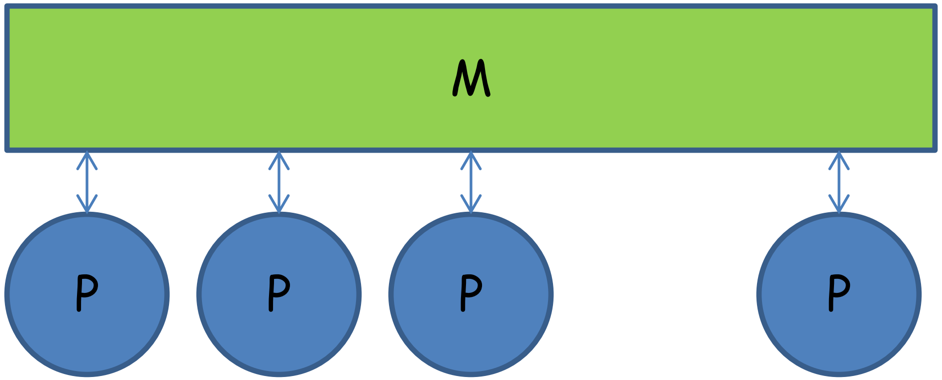
Parallel Computing

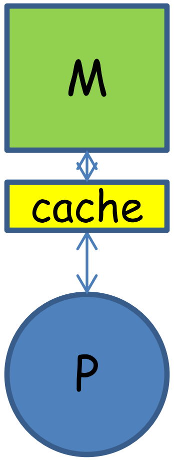
Shared-memory architectures & machines



Shared-memory model

Naive, shared memory (programming) model: processors execute processes, processes are not synchronized, processes exchange information through shared memory, special methods for sharing memory between processes, NUMA but directly visible

Closer to „reality“:



Cache: small, fast memory, close to processor, accessed main memory locations are stored temporarily in cache, reused when possible

Caches may help to alleviate/hide memory („von Neumann“) bottlenect

- Main memory: Gbytes, access times > 100 cycles
- Cache: Kbytes->Mbytes, access times,1-20 cycles

Typically 2-3 levels of caches in modern processors, and several special caches, TLB, victim cache, instruction cache, …

Caches, recap.

Cache consists of a number of lines that stores blocks of memory. A cache line holds a block and additional status information (dirty/valid bit, tag)

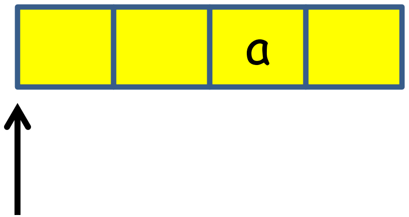
Typical block size: 64Bytes

Caches exploit and makes sense because of:

- Temporal locality: locations are typically used several times in close succession, several operations on same operand
- Spatial locality: when a location is addressed, typically locations close to it (a+1, a+2, …) will be also used

Properties of algorithms/programs, and not always so

Access to main memory in block size units B, aligned to block boundary



B-> cache line

Block boundary

Memory read a:
if address a already in cache, reuse from there, if not read from memory through cache, evict previous line

Memory write a:
different possibilities. If a is already in cache, write overwrites; if a is not in cache

- Write allocate: if a is not in cache, read a
- Write non-allocate: write directly to memory

- Write-through cache: each write is immediately passed on to memory (typically non-allocate)
- Write back: cache line block is written back when line is evicted (typically write allocate)

Address a:

- If a can go into only one specific line of the cache: directly mapped
- If a can go into any line of the cache: fully associative

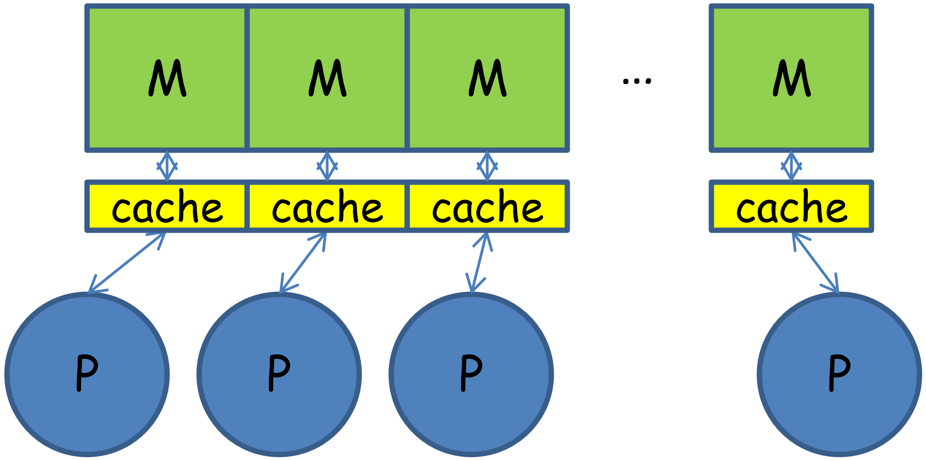
- If a can go into any of a small set of lines: set-associative (typically 2-way, 4-way)

Replacement policies for associative caches

- LRU: least recently used
- LFU : least frequently used

Typically, all maintained in hardware

Multiprocessor/multi-core caches



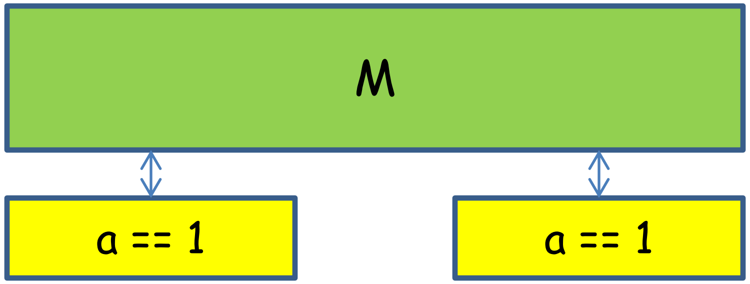
Shared-memory model, cc-NUMA

Cache-coherent non.uniform memory access

Typically, several cores shares caches at some levels

Cache coherence

Processor/core 0 and 1 with private caches, both have read location a into cache. Processor 0 writes to a?



a =7;

b = a; // ??

Read by 1 occurs „after“ write by 0. If b is still 1, cache system is not coherent

Let the order of memory accesses to a specific location a be given by the program order

Cache is coherent if

1. If processor P writes to a at time t1 and reads a at t2>t1, and there are no other writes (by P or other) to a between t1 and t2, then P reads the value written at t1
2. If P1 writes to a at t1 and another P2 reads a at t2>t1 and no other P writes to a between t1 and t2, then P2 reads the value written by P1 at t1
3. If P1 and P2 writes to a at the same time, then either the value of P1 or the value of P2 is stored at a

Ad 1. Program order is preserved for each processor for locations that are not written by other processors

Let the order of memory accesses to a specific location a be given by the program order

Cache is coherent if

1. If processor P writes to a at time t1 and reads a at t2>t1, and there are no other writes (by P or other) to a between t1 and t2, then P reads the value written at t1
2. If P1 writes to a at t1 and another P2 reads a at t2>t1 and no other P writes to a between t1 and t2, then P2 reads the value written by P1 at t1
3. If P1 and P2 writes to a at the same time, then either the value of P1 or the value of P2 is stored at a

Ad 2. Here, t1 and t2 have to be „sufficiently" separated in time. Updates by P1 must eventually become visible to the other processors

Let the order of memory accesses to a specific location a be given by the program order

Cache is coherent if

1. If processor P writes to a at time t1 and reads a at t2>t1, and there are no other writes (by P or other) to a between t1 and t2, then P reads the value written at t1
2. If P1 writes to a at t1 and another P2 reads a at t2>t1 and no other P writes to a between t1 and t2, then P2 reads the value written by P1 at t1
3. If P1 and P2 writes to a at the same time, then either the value of P1 or the value of P2 is stored at a

Ad 3. Writes are required to „serialize". Either of the values simultaneously written will be stored. „Same time" means „sufficiently close" in time.

cc-NUMA systems (most multi-core and SMP nodes): cache coherent, non-uniform memory access

Cache coherence maintained by hardware at the cache line level. Standard approaches and protocols:

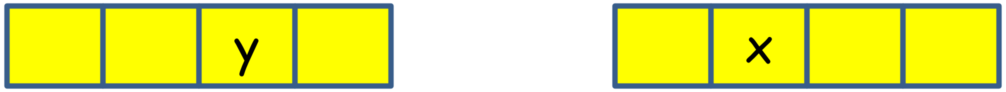
- Update based
- Invalidation based

- Snooping/bus based
- Directory based

All: expensive in hardware („transistors“, „power“); can affect performance negatively

Sharing/false sharing

Cache coherence is maintained at the cache line level. Processor 0 updates y, processor 1 updates x (with e.g. &x == &z[1], &y = &z[2])



```
for (i=0; i<n; i++) y += i-1;
```

```
for (i=0; i<n; i++) x += 2*i;
```

Although x and y are different memory locations, each update will cause cache coherency traffic!! Because cache coherency is at the cache line level, x and y are falsely shared

Memory consistency

In what order do writes to different locations not necessarily in cache become visible in memory and to other processors?

Core 0:

```
x = 0;
// … some code
x = 1;
if (y==0) {
  // body
}
```

Core 1:

```
y = 0;
// … some code
y = 1;
if (x==0) {
  // body
}
```

x not in cache of core 1, y not in cache of core 0

Can core 0 and core 1 both execute body of if-statement?

Core 0:

```
x = 0;
// … some code
x = 1;
if (y==0) {
  // body
}
```

Core 1:

```
y = 0;
// … some code
y = 1;
if (x==0) {
  // body
}
```

If x=1; y=1; appears at the same time, no cores execute body

If core 0 in body, then core 1 has executed y=0; but not y=1; thus core 1 cannot enter body

Correct?

Only under sequential consistency (or similar)

Sequential consistency: memory accesses of each processor are performed in program order; program result is as for some interleaving of the memory accesses of all processors

Sequential consistency is typically not guaranteed by modern multiprocessors:

- Caches, may delay writes
- Write buffers, may delay and/or reorder writes
- Memory network: may reorder writes
- Compiler: may reorder updates

Relaxed consistency models (see other lecture…) pose weaker constraints on hardware, may still allow correctness reasoning

In short:
To guarantee intended effect/correctness of a shared-memory multiprocessor program, special instructions that enforce memory updates to take effect may have to be used

Example:

memory fence(f) : completes all writes before the instruction and sets flag f

Another processor waiting for f will „know" that all writes of the other processor before f was set will have been completed

Other approaches to alleviating memory bottleneck

- Prefetching: start loading operands well before use

- Multi-threading: when a thread („virtual processor“) issues a load, switch to another thread

Note: multi-threading requires explicitly parallel programs

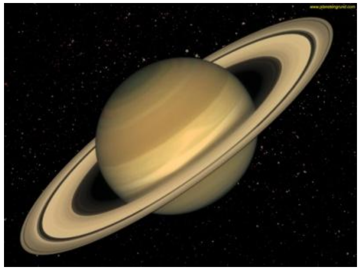
Note: both prefetching and multi-threading are latency hiding techniques. Memory bandwidth is still required for the number of outstanding memory requests

TU Wien parallel computing shared-memory node

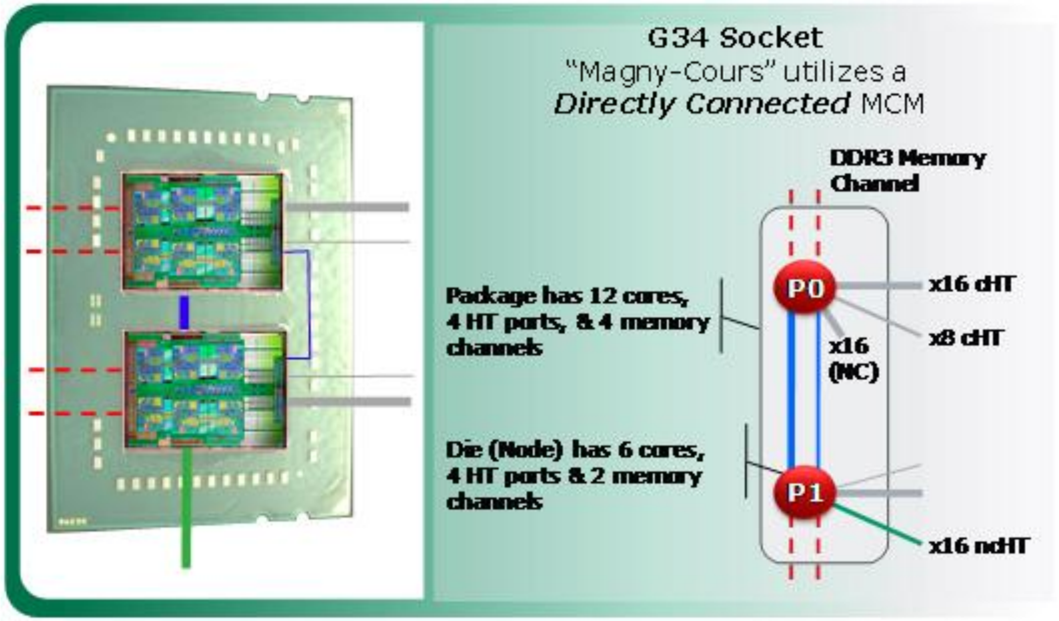
4xAMD „magny cours“ 12-core Opteron 6168 processors
128GByte main memory, 1.9GHz, total number of cores 48

- Per core L1 cache: 128KB
- Per core L2 cache 512KB
- Shared L3 cache 12288KB

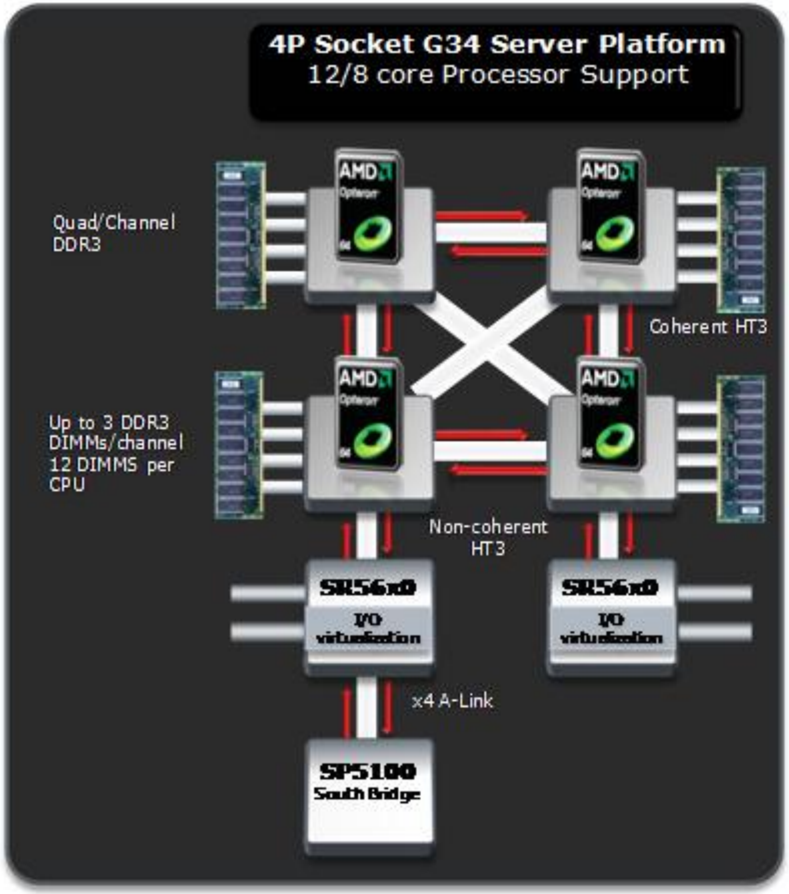
Name:
saturn.par.tuwien.ac.at



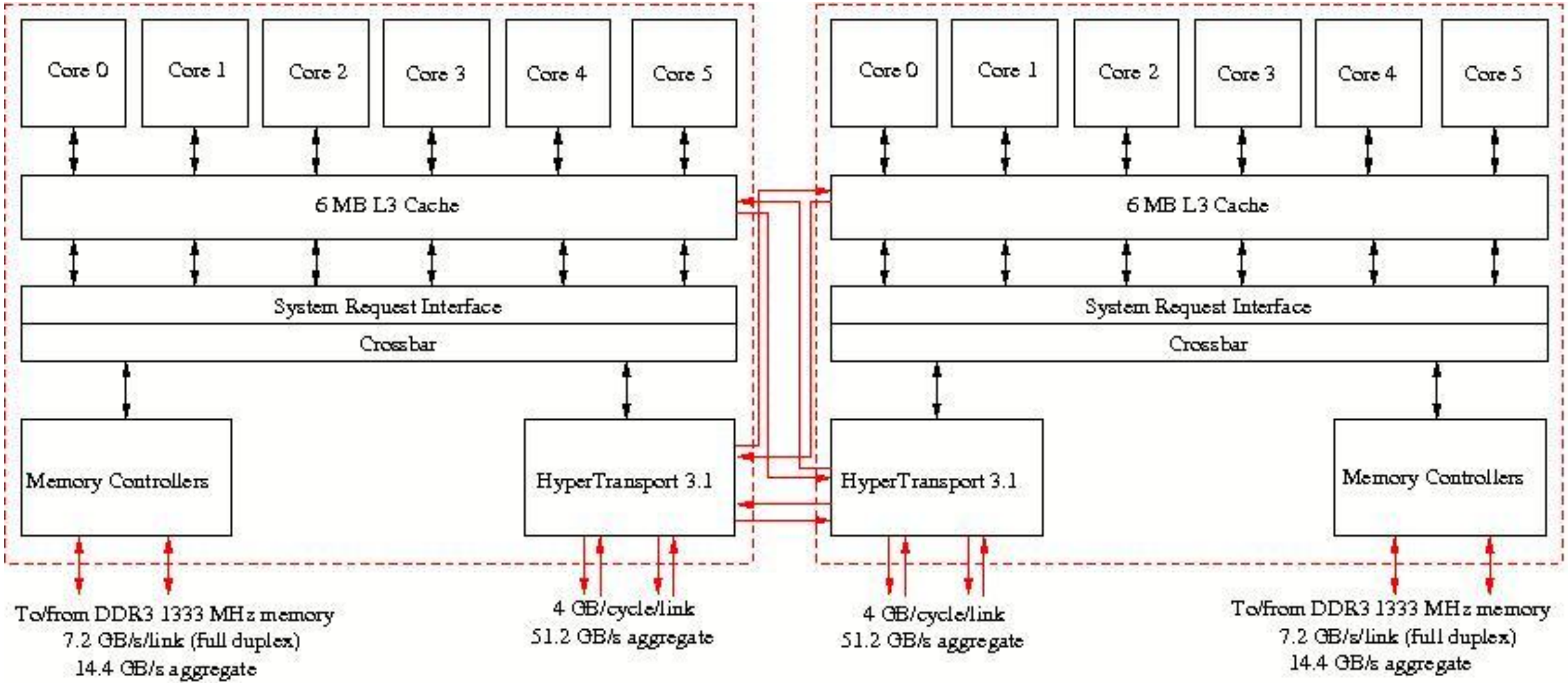
12 core = 2x6 cores, 2 dies on chip?



HT: HyperTransport – standardized processor-processor interconnect

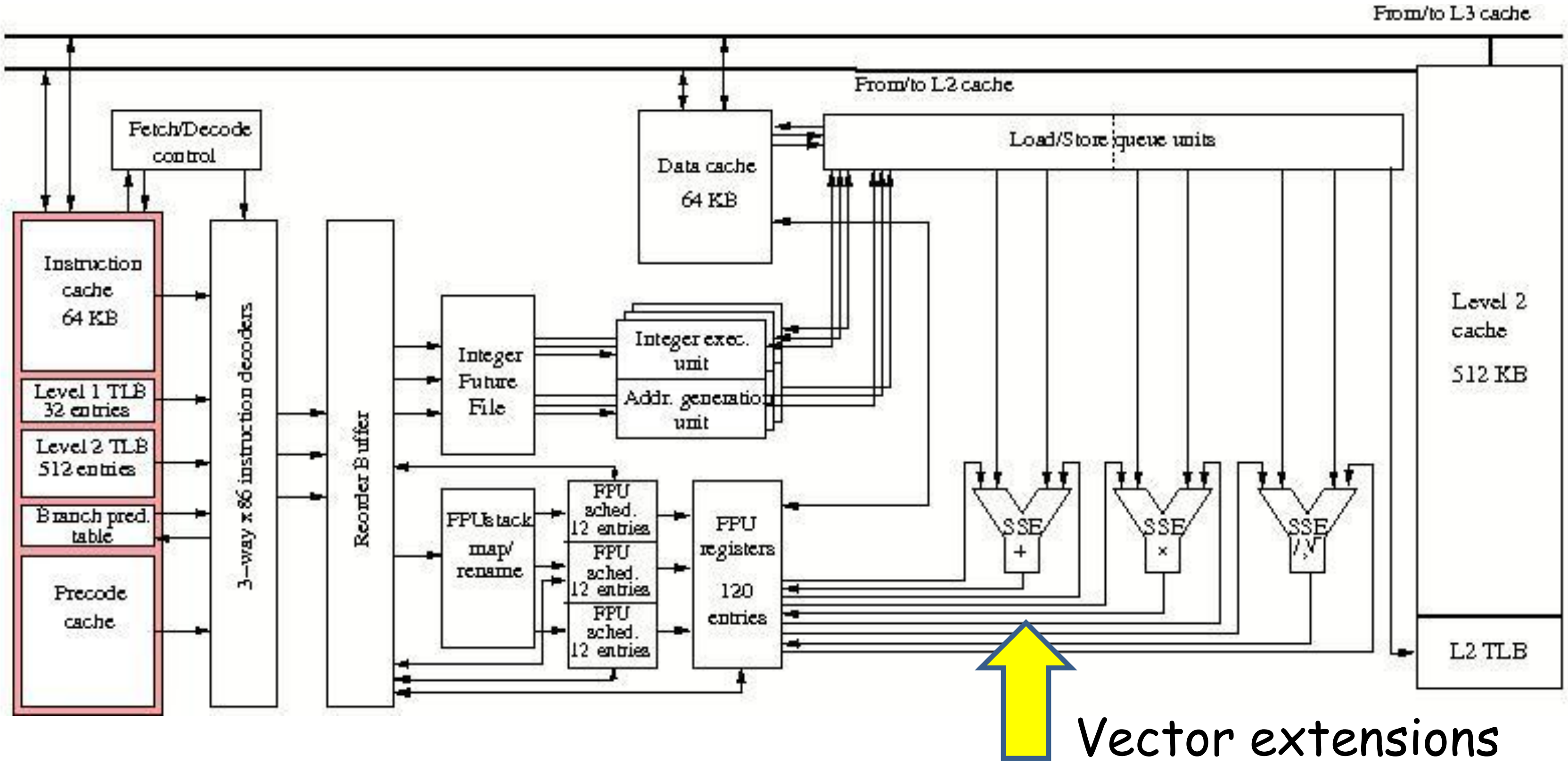

4P Socket G34 Server Platform
12/8 core Processor Support
Quad/Channel DDR3
Up to 3 DDR3 DIMMs/channel 12 DIMMS per CPU
AMD Opteron
Coherent HT3
Non-coherent HT3
SR56x0 I/O virtualization
x4 A-Link
SP5100 South Bridge

48-core shared-memory system from4x12-core



Check-exercise: try to find the (superscalar) issue width? Peak performance? of the Opteron/Magny Cours processor

From University of Utrecht, EuroBen homepage: www.phys.uu.nl/eurben

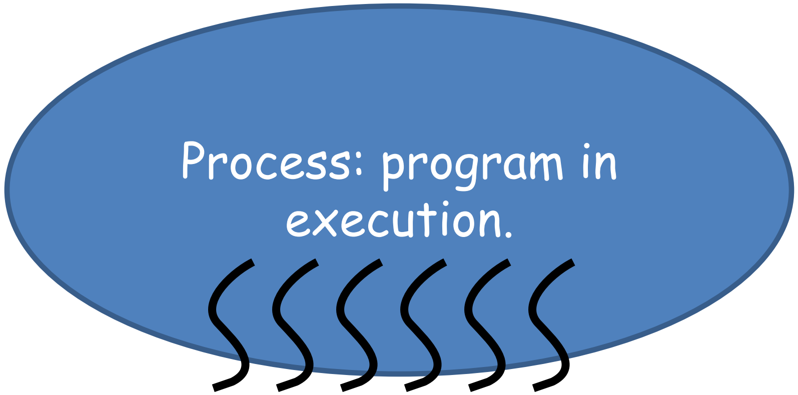


Vector extensions

L1 cache: 64KB data, 64KB instruction

Thread model

Thread: independent stream of instructions that can be scheduled by the OS. Typically, threads live inside an OS „process", and shares all global information of the process (Thread: „smallest unit that can be independently scheduled")



UNIX process global information:

- File pointers
- Global variables
- Static variables
- Heap storage

Per thread: local variables (stack), registers, „thread local storage"

POSIX threads, pthreads

POSIX: Portable Operating Systems Interface for uniX

Standard thread library API for UNIX (Linux etc.) since 1995: IEEE/ANSI 1003.1c-1995

Official standard documents cost money; standard available as man pages, internet, several tutorials and books

Low-level interface for C/UNIX thread programming

More modern thread model, including memory model: Java threads

(p)threads „Programming model"

1. Fork-join type parallelism: a thread can „spawn" (start) any number of new threads (up to system limitations), wait for threads to terminate

2. Initially one main („master") thread is active. Code for thread is a procedure/function

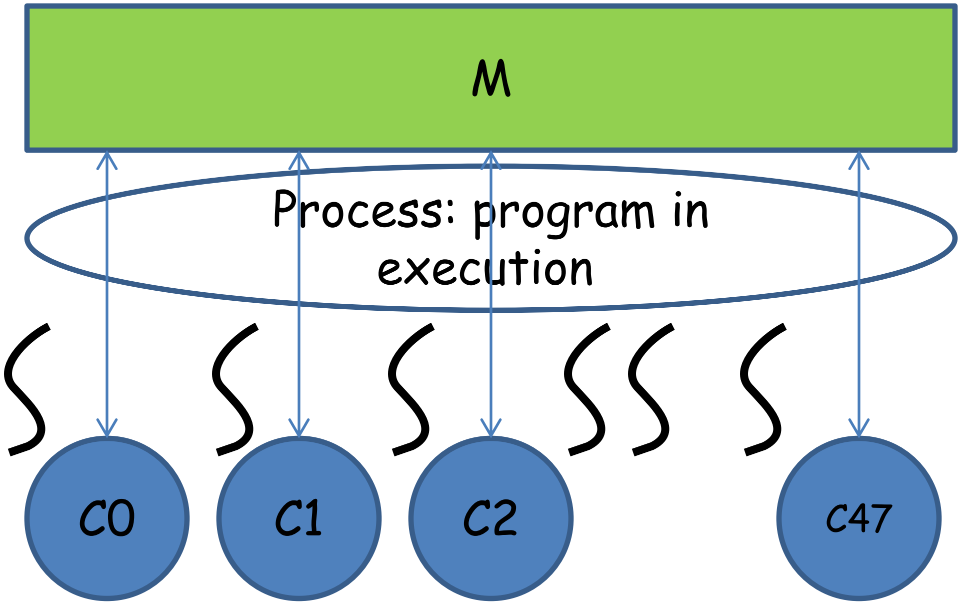
3. Spawned threads are peers, any thread can wait for termination of any other thread

4. Threads are scheduled by the underlying system, may or may not run simultaneously, may or may not be scheduled to available processors/cores

5. No implicit synchronization between threads, threads progress independently, and asynchronously
6. Threads share process global data
7. Coordination mechanisms for protecting access to shared variables (locks, condition variables). All concurrent updates must be protected, otherwise program illegal, outcome undefined
8. …

Pthreads: no cost model, no memory model, …

Pragmatics (for parallel computing): runable threads are expected to be scheduled to free cores. Scheduling and binding (mapping to specific core) can be influenced



pthreads for C:

Main program is main thread, spawns off and waits for termination of additional threads. Thread code: C function

- Include header `<pthread.h>`
- All pthread types and functions prefixed by `pthread_`
- pthread functions return error code, or status information, good practice to check!! (not done here…)

Compile with

```
gcc -Wall -o pthreadshello pthreadshello.c -pthread
```

Starting/spawning a thread

```
#include <pthread.h>

int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void *),
                   void *arg);
```

pthread_t: type of thread object (opaque), thread id returned here (pointer), must be allocated globally by spawning thread

```
static pthread_t newthread
```

Parallel Computing

Starting/spawning a thread

```
#include <pthread.h>

int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void *),
                   void *arg);
```

`void *(start_routine)(void *)`: type template for the function to run as thread. Takes arguments via generic pointer, returns generic pointer, standard C convention

```
void *newcode(void *genericargs) {
  myarg_t realargs = (myarg_t*)genericargs;
  // work to be done by this thread
}
```

Starting/spawning a thread

```
#include <pthread.h>

int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void *),
                   void *arg);
```

`void *`: pointer to arguments, must have beeen allocated by spawning thread in static memory (heap)

```
struct {
  // args
} *
```

Starting/spawning a thread

```
#include <pthread.h>

int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void *),
                   void *arg);
```

Execution of thread can be influenced by attributes: stacksize, scheduling properties, … NULL, or

Not this lecture

```
#include <pthread.h>

int pthread_attr_init(pthread_attr_t *attr);
int pthread_attr_destroy(pthread_attr_t *attr);
```

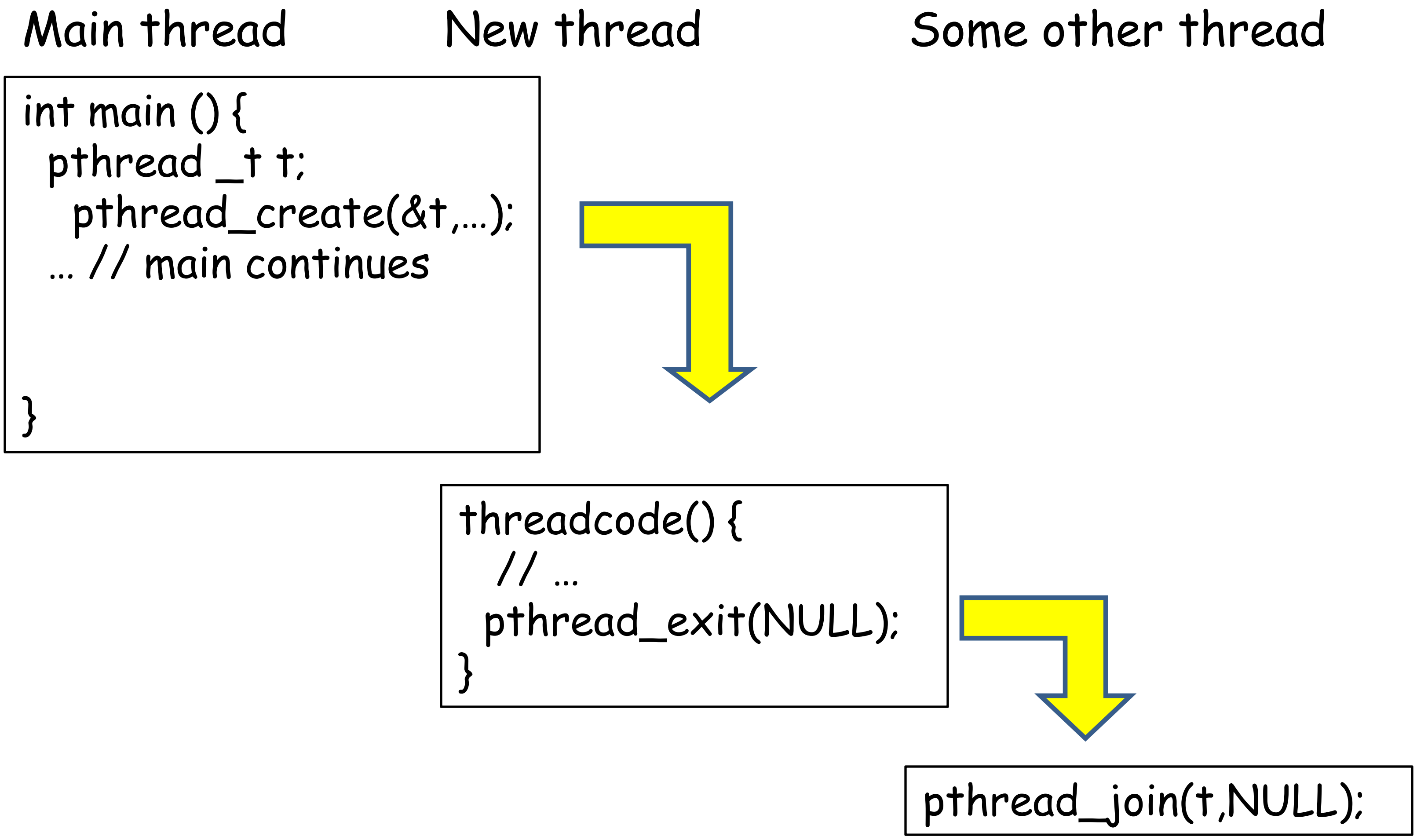
Finalizing/terminating thread

```
#include <pthread.h>

void pthread_exit(void *status);
```

Terminates thread, pointer to return status can be supplied; return status can be caught by joining thread

Joining threads

```
#include <pthread.h>

int pthread_join(pthread_t thread, void **status);
```



Main thread

New thread

Some other thread

```
int main () {
  pthread _t t;
    pthread_create(&t,…);
  … // main continues



}
```

```
threadcode() {
   // …
  pthread_exit(NULL);
}
```

```
pthread_join(t,NULL);
```

A small example

```
#include <stdio.h>
#include <stdlib.h>

// pthreads header
#include <pthread.h>

// global state; here read-only - don‘t do this…
int threads_glob;

void *something(void *argument){
  int rank = (int)argument;

  printf("Thread rank %d of %d responding\n",
         rank,threads_glob);
  pthread_exit(NULL);
}
```

C style: cast void * argument back to intended type

A small example

```
#include <stdio.h>
#include <stdlib.h>

// pthreads header
#include <pthread.h>

// global state; here read-only - don‘t do this…
int threads_glob;

void *something(void *argument){
  int rank = (int)argument;

  printf("Thread rank %d of %d responding\n",
         rank,threads_glob);
  pthread_exit(NULL);
}
```

Here misuse of pointer to store rank

```
int main(int argc, char *argv[]){
  int threads, rank;
  int i;  pthread_t *handle;

  threads = 1;
  for (i=1; i<argc&&argv[i][0]=='-'; i++) {
    if (argv[i][1]=='t')
      i++,sscanf(argv[i],"%d",&threads);
  }
  threads_glob = threads;
  // number of threads read and stored globally

  handle =
    (pthread_t*)malloc(threads*sizeof(pthread_t));
  // fork the threads
  for (i=0; i<threads; i++) {
    pthread_create(&handle[i],NULL,
                   something,(void*)i);
  }
```

Getting command line arguments

Local scalar variable cast into generic void pointer, correct, but dangerous misuse

```
#include <stdio.h>
#include <stdlib.h>

// pthreads header
#include <pthread.h>

// global state; here read-only - don‘t do this…
int threads_glob;

void *something(void *argument){
  int rank = *(int*)argument;

  printf("Thread rank %d of %d responding\n",
         rank,threads_glob);
  pthread_exit(NULL);
}
```

Better: cast and deref

```
int main(int argc, char *argv[]){
  int threads, rank;
  int i;  pthread_t *handle;

  threads = 1;
  for (i=1; i<argc&&argv[i][0]=='-'; i++) {
    if (argv[i][1]=='t')
      i++,sscanf(argv[i],"%d",&threads);
  }
  threads_glob = threads;
  // number of threads read and stored globally

  handle =
    (pthread_t*)malloc(threads*sizeof(pthread_t));
  // fork the threads
  for (i=0; i<threads; i++) {
    pthread_create(&handle[i],NULL,
                   something,&i);
  }
```

Problem?

```
int main(int argc, char *argv[]){
  int threads, rank;
  int i;  pthread_t *handle;

  threads = 1;
  for (i=1; i<argc&&argv[i][0]=='-'; i++) {
    if (argv[i][1]=='t')
      i++,sscanf(argv[i],"%d",&threads);
  }
  threads_glob = threads;
  // number of threads read and stored globally

  handle =
    (pthread_t*)r[illegible](thre[illegible]*s[illegible]zeof(pthread_t));
  // fork the th[illegible]ad[illegible]
  for (i=0; i<th[illegible]ads; [illegible])
    pthread_crea[illegible]&handl[illegible]N[illegible]L,
                         [illegible],&i);
  }
```

Only one (local) variable, may be overwritten befor[illegible]as copied into local

Problem?

Example:
a value (storage of i) is overwritten by one thread, may (or may not) happen before the other threads have read intended value. Program outcome dependent on relative timing of threads. Bad, unintended non-determinism…

Race condition:
Outcome of parallel progam execution is dependent on the relative timing of the updates by processors/threads

```
int main(int argc, char *argv[]){
  int threads, *rank;
  int i;  pthread_t *handle;

  // … get the number of threads
  handle =
    (pthread_t*)malloc(threads*sizeof(pthread_t));
  rank = (int*)malloc(threads*sizeof(int));
  // fork the threads
  for (i=0; i<threads; i++) {
    rank[i] = i;
    pthread_create(&handle[i],NULL,
                   something,&rank[i]);
  }
  // join the threads again
  for (i=0; i<threads; i++) pthread_join(handle[i],NULL);
  free(rank); free(handle);
  return 0;
}
```

Own location for each thread, no overwrite

Free storage nicely

Wait for threads to terminate

#define NDEBUG
// assertion checking disabled

Checking return codes with assertions

Enables assertion checking, macro assert(expr);

```
#include <assert.h>

int main(int argc, char *argv[]){
  int threads, *rank;
  int i;  pthread_t *handle;

  // … get the number of threads, allocate

  // fork the threads
  for (i=0; i<threads; i++) {
    rank[i] = i;
    errcode = pthread_create(&handle[i],NULL,
                             something,&rank[i]);
    assert(errcode==0);
  }
  // …
}
```

Assertion `errcode==0` expected to evaluate to true (≠0), otherwise abort

Potential problem: sequential spawning of treads can limit scalability (Amdahl).

In general: thread creation can be expensive

```
for (i=0; i<threads; i++) {
    rank[i] = i;
    pthread_create(&handle[i],NULL,
                   something,&rank[i]);
  }
  // join the threads again
  for (i=0; i<threads; i++) pthread_join(handle[i],NULL);
```

Fix: spawn recursively

`pthread_t` thread identifiers are opaque; normally user gives thread „identity“ (as in example), a thread can inquire ist own `pthread_t` id; `pthread_t` id‘s can be compared

```
#include <pthread.h>

pthread_t pthread_self(void);
```

```
#include <pthread.h>

int pthread_equal(pthread_t thread_1,
                  pthread_t thread_2);
```

Explicit parallelization of data parallel loop

```
for (i=0; i<n; i++) {
    a[i] = f(i);
}
```

Thread i (on core i) performs

```
for (i=start; i<end; i++) {
    a[i] = f(i);
}
```

start = i*n/threads
end = (i+1)*n/threads

Explicit parallelization of data parallel loop

```
for (i=0; i<n; i++) {
   a[i] = f(i);
}
```

Arguments struct

```
typedef struct {
  int *array;
  // pointer shared, global data
  int start, end;
  int rank; // threads rank
} rankindex_t;
```

```
loopblock(void *what)
{
  rankindex_t *ix = (rankindex_t*)what;
  int *a = ix->array;
  int i, start=ix->start, end=ix->end ;

  for (i=start; i<end; i++) a[i] = f(i);
}
```

Function for loop block

Example: matrix-vector product

y= x*A, nxm matrix x, m vector A

```
for (i=0; i<n; i++) {
  y[i] = 0;
  for (j=0;j<m; j++) {
    y[i] += x[i][j]*A[j];
  }
}
```

Nested loop

Parallelized by tiling outer loop

```
for (i=rank; i<n; i+=threads) {
  y[i] = 0;
  …
```

Each thread rank handles every threads'th index

Thread rank:

```
for (i=rank; i<n; i+=threads) {
  y[i] = 0;
  for (j=0;j<m; j++) {
    y[i] += x[i][j]*A[j];
  }
}
```

Problem?

y[0] = 0;

y[1] = 0;

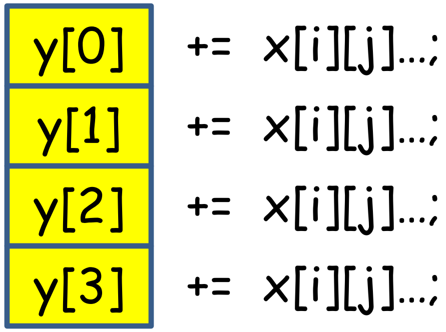
y[2] = 0;

y[3] = 0;

y values go into (local) caches

Thread rank:

```
for (i=rank; i<n; i+=threads) {
  y[i] = 0;
  for (j=0;j<m; j++) {
    y[i] += x[i][j]*A[j];
  }
}
```


y[0] += x[i][j]…;
y[1] += x[i][j]…;
y[2] += x[i][j]…;
y[3] += x[i][j]…;

False sharing: updates on y causes either cache update traffic or invalidates/memory reads

Thread rank:

```
for (i=rank*n/p; i<(rank+1)*n/p; i++) {
  y[i] = 0;
  for (j=0;j<m; j++) {
    y[i] += x[i][j]*a[j];
  }
}
```

Solution?

Exercise: test effects of false sharing (best and worst cases) on TU Wien parallel computing shared-memory node, with explicit thread affinity

Binding threads to cores

```
#define _GNU_SOURCE
#include <pthread.h>

int pthread_setaffinity_np(pthread_t thread,
                           size_t cpusetsize,
                           const cpu_set_t *cpuset);
Int pthread_getaffinity_np(pthread_t thread,
                           size_t cpusetsize,
                           cpu_set_t *cpuset);
```

`_np`: non-portable, non-standard extension to pthreads (but commonly supported in some form)

Thread will be migrated to one of the cores in cpuset

Coordination constructs for avoiding race conditions

- Locks/mutex'es – for ensuring mutual exclusion

- Condition variables

- Advanced, non-standard features: semaphores, barriers, spin locks

Note: these are all classical concurrent computing constructs. Some classical algorithms to solve the problems under weak architecture assumptions: Dekker's algorithm, Lamport's bakery, …

Caution: the constructs were developed for few resources, not necessarily sufficient for highly parallel, scalable programming

Critical section:
Code manipulating shared resources, that must not be concurrently manipulated by other active entities (threads, processes, …)

Shared resources: simple variables, data structures, devices

Mutual exclusion property/algorithm: at most one thread in given critical section

Pthread „model": it is not allowed to update shared variables outside of critical sections. The lock constructs shall ensure a consistent view of memory.

Locks

Lock: shared object between any number of threads.

Lock state: locked (acquired), or unlocked (released)

At most one thread can acquire the lock, must release after use. When a thread attempts to acquire a lock that is already acquired by another thread it is blocked, and waits until the lock is released

If any thread that is waiting to acquire a lock is eventually granted the lock, the lock is called fair!!

Pthread lock is called mutex, type `pthread_mutex_t`

Static allocation and initialization with

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
```

Dynamically allocated mutexes

```
#include <pthread.h>

Int pthread_mutex_init(pthread_mutex_t *mutex,
                       const pthread_mutex_attr *attr);
```

```
#include <pthread.h>

int pthread_mutex_destroy(pthread_mutex_t *mutex);
```

Locking and unlocking

```
#include <pthread.h>

int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

Unsafe program, what is the intended value of x for thread 0 and 1?

```
x = 0;
```

Thread 0:

```
a = x;
```

Thread 1:

```
b = x;
```

Thread 2:

```
x = c;
```

Race condition: depends on relative timing of threads

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
```

Thread 0:

```
lock(&lock);
a = x;
unlock(&lock);
```

Thread 1:

```
lock(&lock);
b = x;
unlock(&lock);
```

Thread 2:

```
lock(&lock);
x = c;
unlock(&lock);
```

Mutual exclusion ensured – enforced by locking

Both read and write accesses to x need to be protected by the lock mutex

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
```

Thread 0:

```
lock(&lock);
a = x;
unlock(&lock);
```

Thread 1:

```
lock(&lock);
b = x;
unlock(&lock);
```

Thread 2:

```
lock(&lock);
x = c;
unlock(&lock);
```

Mutual exclusion ensured – enforced by locking

Note: pthread locks are not fair, no guarantee that a thread trying to acquire a lock will eventually acquire it

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
```

Thread 0:

```
lock(&lock);
lock(&lock);
a = x;
unlock(&lock);
```

Deadlock!

Thread 1:

```
lock(&lock);
b = x;
unlock(&lock);
```

Thread 2:

```
lock(&lock);
x = c;
unlock(&lock);
```

Deadlock: two or more threads are in a situation where they dependently on each other cannot progress. Deadlock will eventually proliferate to all threads

What about this?

Thread 0:	Thread 1:	Thread 2:
`a = f(x);`	`b = f(x);`	`c = f(y);`

No apparent races, independent evaluation of some function f

OK?

Depends on f, must be such that it can indeed be executed concurrently: „tread safe“

Thread safety

Tautological definition: a function is thread-safe if it can be executed concurrently by any number of threads and will always produce correct results

Non-thread safe functions are

1. Functions that do not protect (write access) to shared variables
2. Functions that keep state over successive invocations (`static` variables).
3. Functions that return pointers to `static` variables
4. Functions that call thread-unsafe functions

Careful with functions supplied by other party, e.g. system functions

Example: `rand()` keeps state internally in static variables, notoriously not thread safe

Some system functions are made thread safe by locking. Can have undesirable effects – serialization slowdown, deadlock

More on locks

Testing and getting lock/non-blocking lock

```
#include <pthread.h>

int pthread_mutex_trylock(pthread_mutex_t *mutex);
```

If `mutex` is not held by other tread, lock acquired; if already held by other thread `EBUSY` is returned, calling thread is not blocked

Dead-locks:

```
pthread_mutex_t lock1 = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_t lock2 = PTHREAD_MUTEX_INITIALIZER;
```

Thread 0:

```
…
pthread_mutex_lock(&lock1);
pthread_mutex_lock(&lock2);
…
```

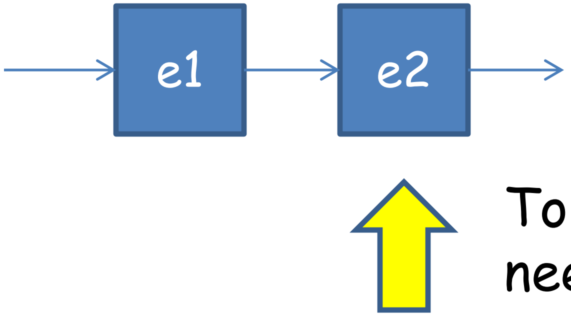
Thread 1:

```
…
pthread_mutex_lock(&lock2);
pthread_mutex_lock(&lock1);
…
```

Can – and will – lead to deadlock!!

Beware: even the most „unlikely“ deadlock situation will eventually happen! Design correct programs…

Multiple locks, example: list processing



To remove e2, may
need lock on e1 and e2

Problem with locks: code for different threads may have been written with different locking conventions, by different people, at different times…

More flexible locks: reader/writer locks

Allow several threads to acquire lock for reading shared variables, single thread to acquire for writing

```
#include <pthread.h>

int pthread_rwlock_init(pthread_rwlock_t *rwlock,
              const pthread_rwlockattr_t *attr);
```

```
#include <pthread.h>

int pthread_rwlock_destroy(pthread_rwlock_t *rwlock);
```

```
#include <pthread.h>

int pthread_rwlock_rdlock(pthread_rwlock_t *rwlock);
int pthread_rwlock_wrlock(pthread_rwlock_t *rwlock);

int pthread_rwlock_unlock(pthread_rwlock_t *rwlock);

int pthread_rwlock_tryrdlock(pthread_rwlock_t *rwlock);
int pthread_rwlock_trywrlock(pthread_rwlock_t *rwlock);
```

```
pthread_rwlock_t lock = PTHREAD_RWLOCK_INITIALIZER;
```

Thread 0:

```
rdlock(&lock);
a = x;
unlock(&lock);
```

Thread 1:

```
rdlock(&lock);
b = x;
unlock(&lock);
```

Thread 2:

```
wrlock(&lock);
x = c;
unlock(&lock);
```

Thread 0 and 1 can both enter their critical section simultaneously, thread 2 can only alone be in its critical section

```
pthread_rwlock_t lock = PTHREAD_RWLOCK_INITIALIZER;
```

Thread 0:

```
rdlock(&lock);
a = x;
unlock(&lock);
```

Thread 1:

```
rdlock(&lock);
b = x;
unlock(&lock);
```

Thread 2:

```
wrlock(&lock);
x = c;
unlock(&lock);
```

Note: pthread locks are not fair, no guarantee that a thread trying to acquire a lock will eventually acquire it

More lock flexibility: condition variables

Thread may temporalily relinquish lock, and wait (suspend) for condition-signal

```
#include <pthread.h>

int pthread_cond_init(pthread_cond_t *cond,
                      const pthread_cond_attr *attr);
int pthread_cond_destroy(pthread_cond_t *cond);
```

Wait for signal on condition variable inside critical section

```
#include <pthread.h>

int pthread_cond_wait(pthread_cond_t *cond,
                      pthread_mutex_t *mutex);
```

Thread suspended (waits), lock is temporarily relinquished. When thread it later resumed (woken up) by a signal from some other thread, it has again acquired lock

Good practice: recheck whether wait-condition is fulfilled

Deadlock: threads mutually wait on some condition, no thread signals

Wait for signal on condition variable inside critical section

```
#include <pthread.h>

int pthread_cond_wait(pthread_cond_t *cond,
                      pthread_mutex_t *mutex);
```

Thread suspended (waits), lock is temporarily relinquished. When thread it later resumed (woken up) by a signal from some other thread, it has again acquired lock

Good practice: recheck wheter wait-condition is fulfilled.

There can be spurious wakeups – threads signaled wrongly or getting a signal spuriously from pthreads

Signal some waiting thread

```
#include <pthread.h>

int pthread_cond_signal(pthread_cond_t *cond);
```

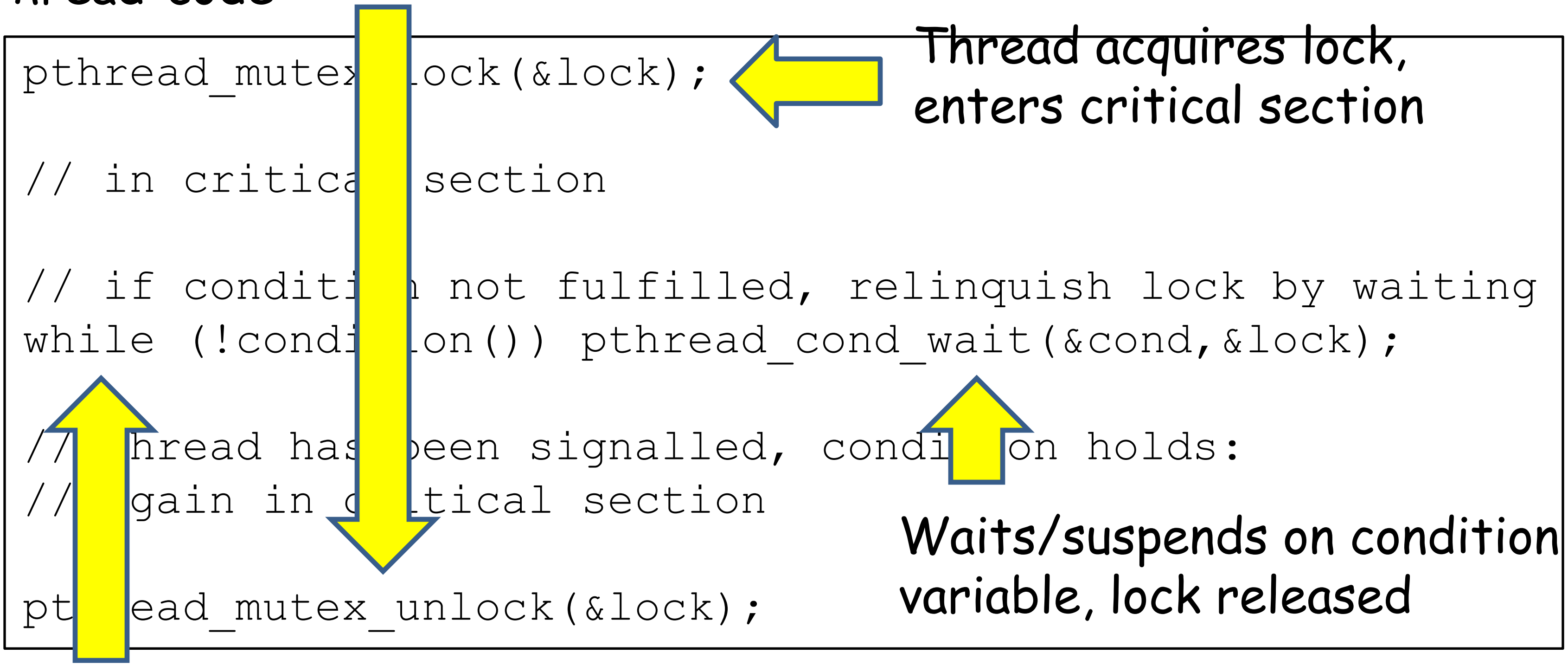
Signal all waiting threads

```
#include <pthread.h>

int pthread_cond_broadcast(pthread_cond_t *cond);
```

If more than one thread is waiting, which gets signal is undetermined (can be influenced by attributes); broadcast signals one after another

Standard condition variable pattern

Thread-code



```
pthread_mutex_lock(&lock);

// in critical section

// if condition not fulfilled, relinquish lock by waiting
while (!condition()) pthread_cond_wait(&cond,&lock);

// thread has been signalled, condition holds:
// again in critical section

pthread_mutex_unlock(&lock);
```

Thread releases lock normally

Thread acquires lock, enters critical section

Waits/suspends on condition variable, lock released

After signal, lock is again acquired (mutual exclusion!), condition can be rechecked

Example: readers-writers lock with condition variables

Idea:
Keep track of number of readers, pending writers, whether there is a writer, condition variables to suspend readers and writers trying to acquire lock, standard mutex for ensuring mutual exclusion to the shared data structure

```
typedef struct {
  int readers;
  int waiting, writer;
  pthread_cond_t read_ok, write_ok;
  pthread_mutex_t gateway;
} rwlock_t;
```

Init function: no readers, no writer, no pending; initialize mutex and condition variables

Acquire reading lock

```
void rwlock_rlock(rwlock_t *rwlock)
{
  pthread_mutex_lock(&rwlock->gateway);
  while (rwlock->waiting>0||rwlock->writer) {
    pthread_cond_wait(&rwlock->read_ok,
                      &rwlock->gateway);
  }
  rwlock->readers++;
  pthread_mutex_unlock(&rwlock->gateway);
}
```

Acquire single writing lock

```
void rwlock_wlock(rwlock_t *rwlock)
{
  pthread_mutex_lock(&rwlock->gateway);
  rwlock->waiting++;
  while (rwlock->writer||rwlock->readers>0) {
    pthread_cond_wait(&rwlock->writer_ok,
                      &rwlock->gateway);
  }
  rwlock->waiting--;
  rwlock->writer = 1;
  pthread_mutex_unlock(&rwlock->gateway);
}
```

Unlock: wake up threads waiting to acquire lock

```
void rwlock_ulock(rwlock_t *rwlock)
{
  pthread_mutex_lock(&rwlock->gateway);
  if (rwlock->writer) rwlock->writer = 0;
  else rwlock->readers--;
  pthread_mutex_unlock(&rwlock->gateway);

  // resume threads waiting to acquire
  if (rwlock->readers==0&&rwlock->waiting>0) {
    pthread_cond_signal(&rwlock->writer_ok);
  } else pthread_cond_broadcast(&rwlock->reader_ok);
}
```

Signal can be sent outside critical section

But actually race: readers/waiting can be changed by other threads after unlock

Correctness:
Establish (prove) invariants: readers counts the number of threads having acquired read lock, writer is true if and only if a process has acquired write lock, etc.

Note: the original implementation from <book?> was not correct at all

(Un)Fairness properties:
Threads acquiring write lock can starve threads wanting to acquire read lock (??)

- Newer writer can starve older writer
- Newer reader can acquire lock before older reader – or writer

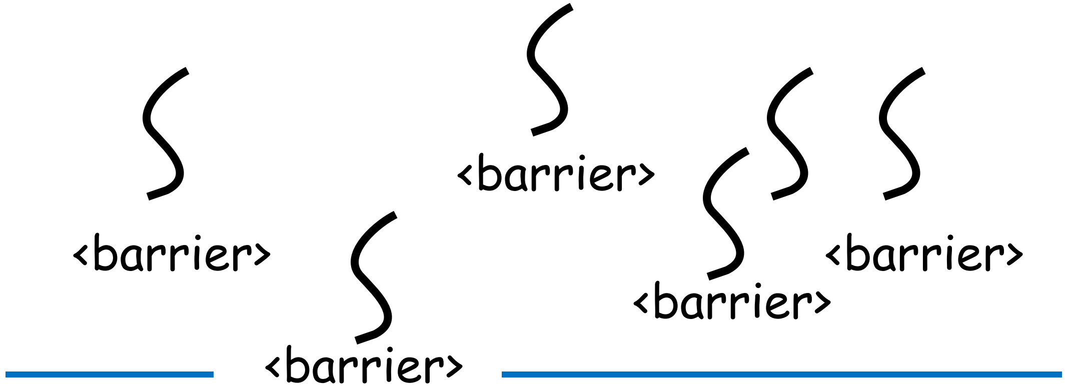
Unlock: wake up threads waiting to acquire lock

```
void rwlock_ulock(rwlock_t *rwlock)
{
  pthread_mutex_lock(&rwlock->gateway);
  if (rwlock->writer) rwlock->writer = 0;
  else rwlock->readers--;

  // resume threads waiting to acquire
  if (rwlock->readers==0&&rwlock->waiting>0) {
    pthread_cond_signal(&rwlock->writer_ok);
  } else pthread_cond_broadcast(&rwlock->reader_ok);

  pthread_mutex_unlock(&rwlock->gateway);
}
```

Thread signals but keeps lock; signals sent after lock release

Example: Barrier synchronization with condition variables

Each thread execution <barrier> shall wait until all/some number of threads have executed <barrier>



Threads can proceed

Naive barrier

```
typedef struct {
  int tc; // thread count
  pthread_cond_t barrier_ok;
  pthread_mutex_t barwait;
} barrier_t;
```

Also from <book?>

```
void barrier(barrier_t  *b, int tc)
{
  pthread_mutex_lock(&b->barwait);
  b->tc++;
  if (b->tc==tc) {
    b->tc =0;
    pthread_cond_broadcast(&b->barrier_ok);
  else pthread_cond_wait(&b->barrier_ok,&b->barwait);
  pthread_mutex_unlock(&b->barwait);
}
```

Note:

1. This barrier implementation is not scalable, O(p)
2. Probably not safe on spurious wake ups
3. Other problems

Fixes:

1. Tree structured barrier
2. Extra flag

[Mellor-Crummey, Scott: Algorithms for Scalable Synchronization on Shared-Memory Multiprocessors. ACM TOPLAS (1): 21-65 (1991)]

Spin locks – specific implementation for performance

```
#include <pthread.h>

int pthread_spin_destroy(pthread_spinlock_t *lock);
int pthread_spin_init(pthread_spinlock_t *lock,
                      int pshared);
```

Mutex semantics, but different pragmatics/implementation/performance

```
#include <pthread.h>

int pthread_spin_lock(pthread_spinlock_t *lock);
int pthread_spin_trylock(pthread_spinlock_t *lock);
```

Pragmatics/implementation:
thread waiting to acquire lock does not suspend, waits for lock release by „spinning“ on flag

Contrast: mutex locks, thread blocking on lock may be suspended (put to sleep) by OS, and resumed when lock is released

```
#include <pthread.h>

int pthread_spin_unlock(pthread_spinlock_t *lock);
```

Hint:

Hand-implemented locks, or other data structure requiring waiting – useful to suspend thread and yield processor to some other thread

```
#include <sched.h>

int sched_yield(void);
```

Spinlocks: possibly faster on dedicated (parallel) applications on dedicated systems, expensive OS suspension not required.

On overloaded systems – more threads than cores/processors – spinlocks can behave very badly

Portability caveat:
to enforce „spinning" behavior, explicit use of spinlocks needed, program needs rewrite/recompilation/conditional compilation.

Why not controlled by mutex-attributes?

Example: coming to terms without locks

Task: find all primes between 2 and 10^9

Idea: first independently, and in parallel, check all 10^9-1 candidates

Observation: check very fast for some numbers – those with a small prime factor; also, the number of primes in different intervals differ, by prime number theorem

Note: for illustration purposes only, for better ideas see [Crandall, Pomerance: Prime numbers. Springer, 2002]

Statically scheduled data parallel loop will likely lead to load imbalance

```
for (i=2; i<1000000000; i++) {
  if (isPrime(i)) printf(„Found %d\n“,i);
}
```

Static schedule: each thread executes block of 1000000000/p successive iterations

If a few of the processors execute only the expensive isPrime checks, Tpar will be close to Tseq, no Speedup

Better solution: use a shared, global counter

```
int i = 0; // shared global

// Thread i code
while (i<1000000000) {
  int j = i; i++; // thread gets next value of i
  if (isPrime(j)) printf(„Found %d\n“,j);
}
```

Problem?

`i++;` translates into

```
tmp = i;
tmp = tmp+1;
i = tmp;
```

Thread 0:

```
tmp = i;

tmp = tmp+1;
i = tmp;
```

Thread 1:

```
tmp = i;

tmp = tmp+1;
i = tmp;
```

Both threads reads same value for i

`i` incremented by 1 only – race condition!!

Better solution: use a shared, global counter

```
int i = 0; // shared global

// Thread i code
while (i<1000000000) {
  int j;
  pthread_mutex_lock(&counter);
  j = i; i++;
  pthread_mutex_unlock(&counter);
  if (isPrime(j)) printf(„Found %d\n“,j);
}
```

Problem?

Better solution: use a shared, global counter

Thread 0

```
int i = 0; // shared global

// Thread i code
while (i<1000000000) {
  int j;
  pthread_mutex_lock(&counter);
  j = i; i++;




  pthread_mutex_unlock(&counter);
  if (isPrime(j)) printf(„Found %d\n“,j);
}
```

Thread 0 acquired lock, may be interrupted for arbitrarily long time; no progress

Better solution: use a shared, global counter with atomic increment

```
int i = 0; // shared global

// Thread i code
while (i<1000000000) {
  int j = fetch_and_inc(&i); // return value of i, inc
  if (isPrime(j)) printf(„Found %d\n“,j);
}
```

Correct. Threads can always progress

Example of lock-free algorithm: each thread will always be able to progress – no matter what other threads are doing

Atomic instructions in modern multi-core processors

- fetch-and-inc(a): atomically return old value of a, increment
- fecth-and-dec(a): atomically return old value of a, decrement

- fetch-and-add(a,x): atomically return old value of a, add x to a

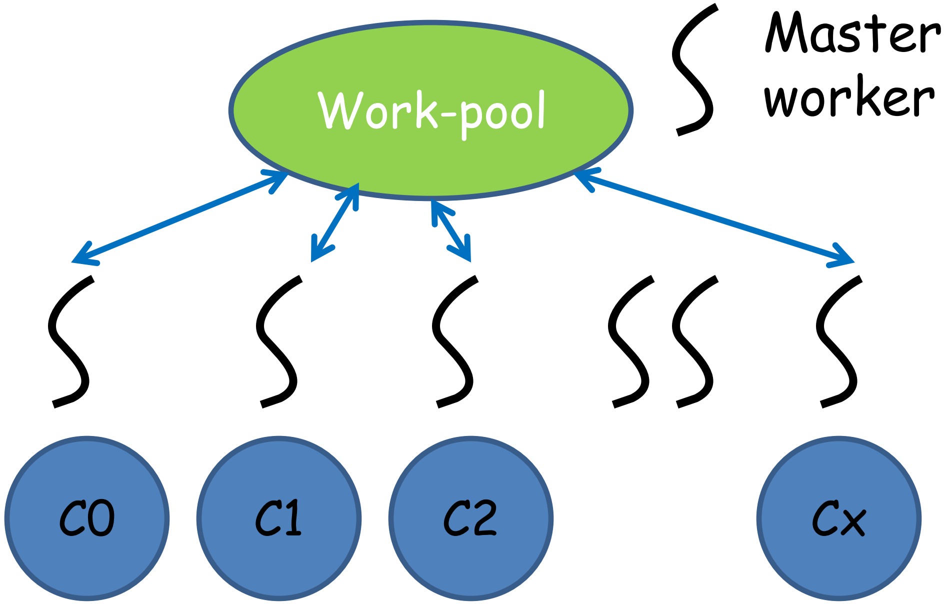
- test-and-set/compare-and-swap (e,u,a): if content of a is equal to e, replace content of a with u, atomically

- LL/SC

See: [Herlihy, Shavit: The Art of Multiprocessor Programming. Morgan Kaufmann, 2008]

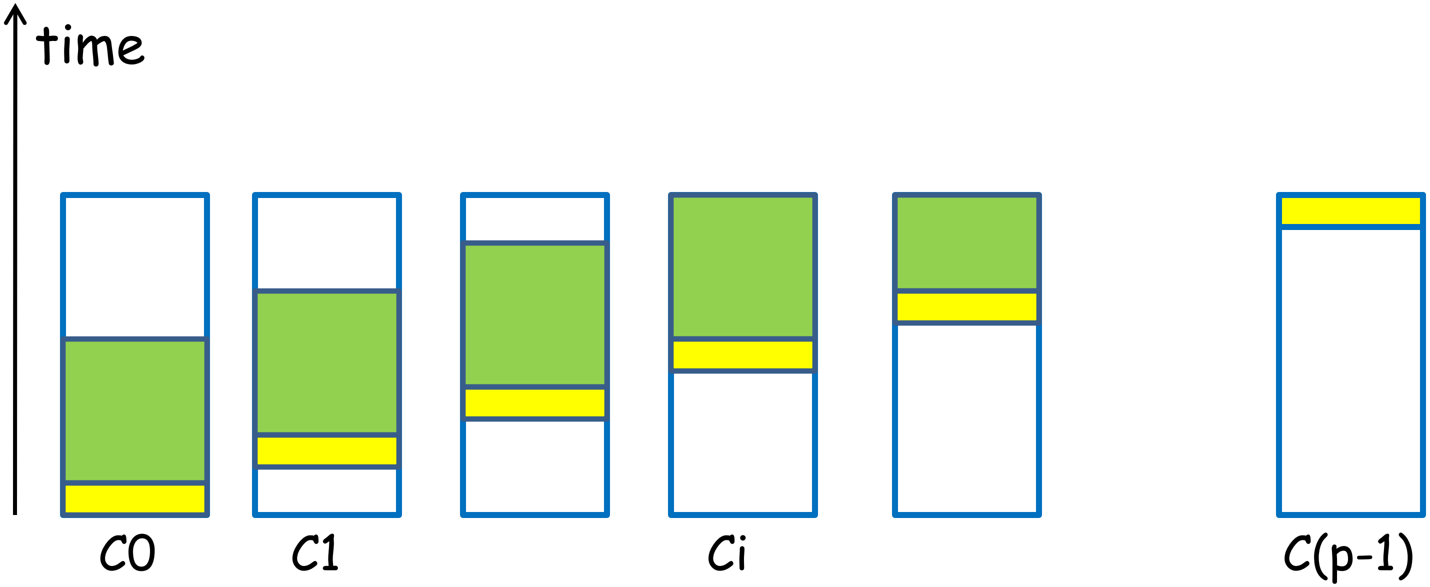
Work-pools, master-worker paradigm

„Master maintains pool of work, workers ask for work, execute, return new work/results to master, until all done“



Master thread: master-worker paradigm

Master/Work-pool possible scalability bottleneck



🟨 Getting work: explicitly asking master, or accessing shared data structure

Implementation sketch, work executed in generated order

Use deque data structure as work-pool

Threads:

1. Acquire mutex, check list, if non-empty take from front, otherwise wait on condition variable.

2. Execute work.

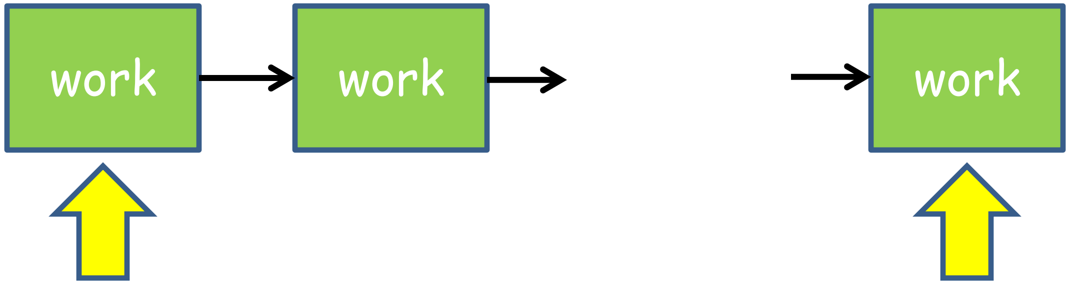
3. New work: acquire mutex, insert at end of deque, wake up waiting threads

Until termination

General work-task structure

```
typedef struct work {
  void (*routine)(void *args);
  void *args;
  struct work *next;
} work_t;
```

Work pool: linked list, first and last element



Task parallel algorithms use work-pool-like implementation to keep threads busy executing tasks

```
void QuickSort(int x[],n) {
  if (n<=1) return;

  pivot = choosepivot(x,n); // x[pivot] is pivot element
  ix = partition(x,pivot); // ix is index of pivot after
  spawn QuickSort(x,ix); // recurse
  spawn QuickSort(x+ix+1,n-1-ix);
}
```

Spawned task may execute in parallel on other core

With linear partition and optimal pivot parallel time is O(n+n/2+n/4+…) = O(n) – with p O(log n) cannot do better

Problems:

1. Centralized resource, bad for scalability

2. Locks: thread updating shared resource can lock out all other threads indefinitely

Work-stealing: Cilk, TBB, …

Solutions:

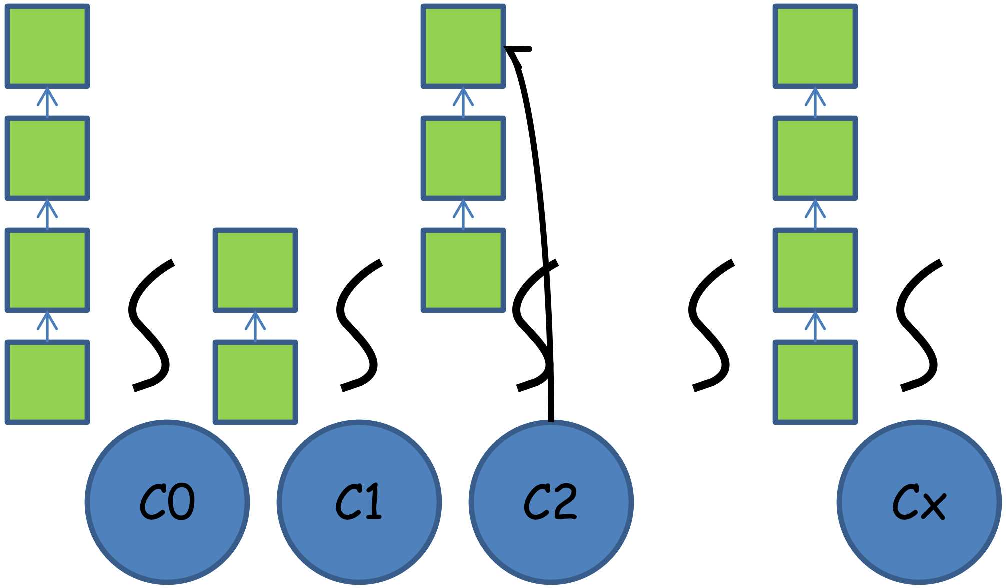
1. Local task queues, a thread primarily uses local queue, when empty steals some work from some other thread's queue

2. Lock-free data structures enabling a thread always to either make progress by itself, or ensure that some other thread is making progress

[Robert D. Blumofe, Charles E. Leiserson: Scheduling Multithreaded Computations by Work Stealing. J. ACM 46(5): 720-748 (1999)]

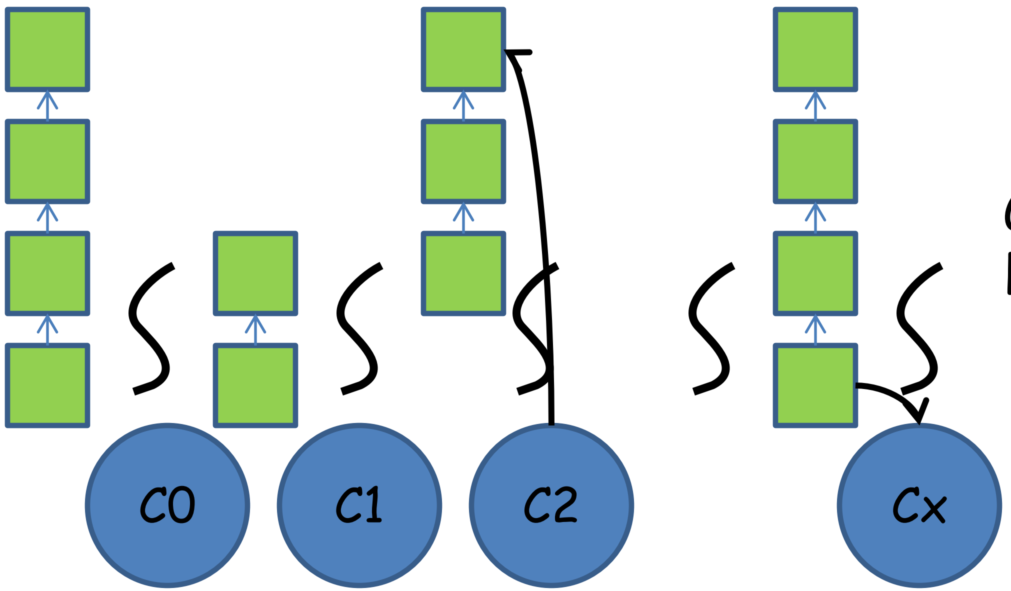
Local dequeues

Put new work in local queue



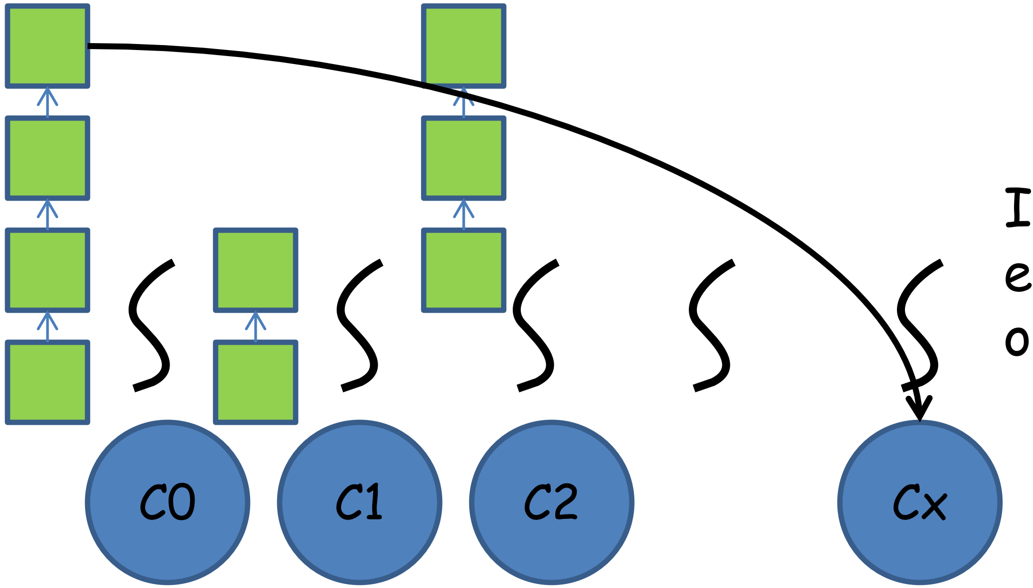
Local dequeues

Put new work in local queue



Get work from local queue

Randomized stealing: good theoretical properties, O(d+W/p) with high probability under certain conditions, d: depth, W: work



If local queue empty, steal from other thread

Deterministic stealing: can provide good locality properties

Solutions:
Lock-free data structures (deques, stacks, …) make extensive use of strong atomic operations: CAS (compare-and-swap)

Caution:

To lock or not to lock for performance: difficult, practical issue, application and system dependent

Lock-free data structures: active research area, practical and theoretical issues and challenges

See: master lecture on advanced multiprocessor programming

OpenMP

Standard for (mostly) data parallel shared-memory programming in C/C++/Fortran, „Open Multi-Processing"

Developed by group of vendors/compiler companies, univesities, users. Official standard since 1997, maintained by A(chitecture) R(eview) B(oard) , non-profit organization owning the OpenMP trademark

Latest release of standard: OpenMP 3.1, July 2011

See www.openmp.org

Also www.compunity.org

ARB Permanent Members:

- AMD
- Cray
- Fujitsu
- HP
- IBM
- Intel
- NEC
- The Portland Group, Inc.
- Oracle Corporation
- ORNL
- Microsoft
- Texas Instruments
- CAPS-Entreprise
- NVIDIA

Auxiliary Members:

- ANL
- ASC/LLNL
- cOMPunity
- EPCC
- LANL
- NASA
- RWTH Aachen University
- Texas Advanced Computing Center

Chair of Language committee: Bronis de Supinski, LLNL

Basic idea:

- Provide for gradual parallelization of C/Fortran programs by identifying constructs – loops - where parallelism can easily be exploited
- Constructs and type of parallelism identified by language-pragmas (and a few library operations)

➡

- Requires compiler support
- Idea: a correct OpenMP program is always a correct sequential program (library calls may have to be replaced)

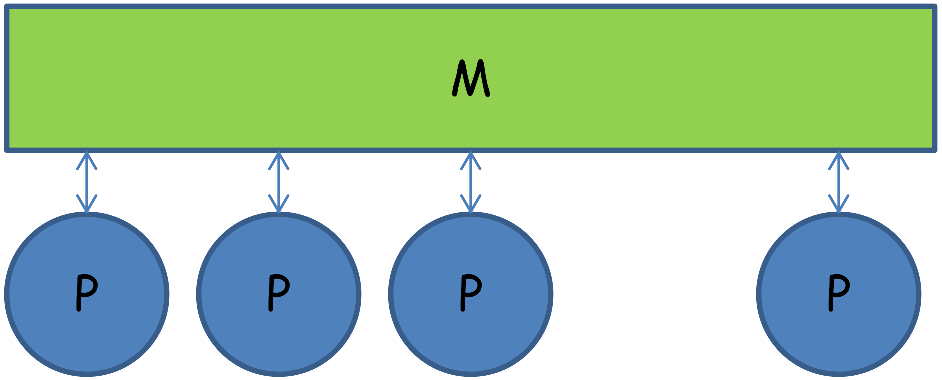
Most C/Fortran compilers now support OpenMP

- GNU gcc

- Intel (one of the first to fully support OpenMP)
- IBM
- Portland Group
- Microsoft
- HP
- Cray
- …

Lack of/bad compiler support did for some years limit use of OpenMP. Efficient support of OpenMP probably not trivial

OpenMP architecture model



Naive, flat, shared-memory model, processors-memory, no explicit cost-model, UMA

OpenMP programming model

1. Parallelism is (mostly) implicit
2. Fork-join parallelism: master thread implicitly spawns threads through OpenMP construct (pragma), threads join at end of construct
3. Number of threads limited by number of processors/cores
4. Threads intended to be executed in parallel by available cores/processors
5. Work of OpenMP construct divided across threads

6. Threads can share variables; shared variables are shared among all threads

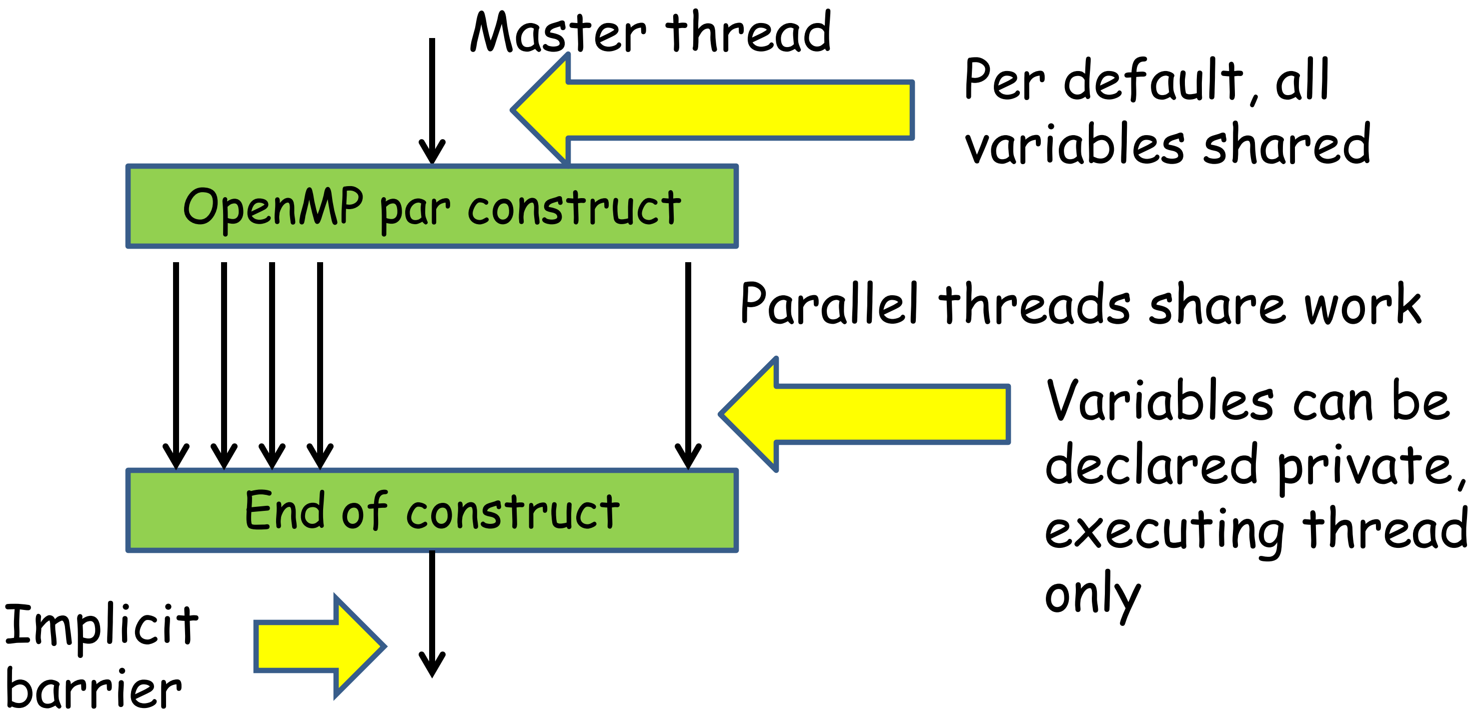
7. Threads can have private variables

8. Unintended updates of shared variables can lead to race conditions

9. Synchronization constructs for preventing race conditions

10. OpenMP 3.0: task model

Not this lecture



Master thread

Per default, all variables shared

OpenMP par construct

Parallel threads share work

Variables can be declared private, executing thread only

End of construct

Implicit barrier

Data transfer between shared and private (copies) variables is transparent, implicit

OpenMP for C:

- Include header `<omp.h>`

- OpenMP constructs identified by `#pragma <directive> [clauses]`

- Some library routines for getting number of threads, synchronization mechanisms, …

- Library routines prefixed by `omp_`

- Macro `_OPENMP` defined (to version date) for conditional compilation

Compile with

```
gcc -Wall  -fopenmp -o openmphello -O3 openmphello.c
```

OpenMP for Fortran:

- OpenMP constructs surrounded by `!$OMP <directive> [clauses]`

Not this lecture

1st example

```c
#include <stdio.h>
#include <stdlib.h>

#include <omp.h> // OpenMP header

int main(int argc, char *argv[]) {
  int threads, myid;
  int i;  threads = 1;

  for (i=1; i<argc&&argv[i][0]=='-'; i++) {
    if (argv[i][1]=='t') sscanf(argv[++i],"%d",&threads);
 }

 printf("Maximum number of threads possible is %d\n",
        omp_get_max_threads());
  // …
}
```

OpenMP library call

Normally some small multiple of number of physical processors/cores

```
int main(int argc, char *argv[]){
   int threads, myid;
  int i;  threads = 1;

  // …

  if (threads<omp_get_max_threads()) {
    if (threads<1) threads = 1;
    omp_set_num_threads(threads);
 } else {
    threads = omp_get_max_threads();
  }

  // …
}
```

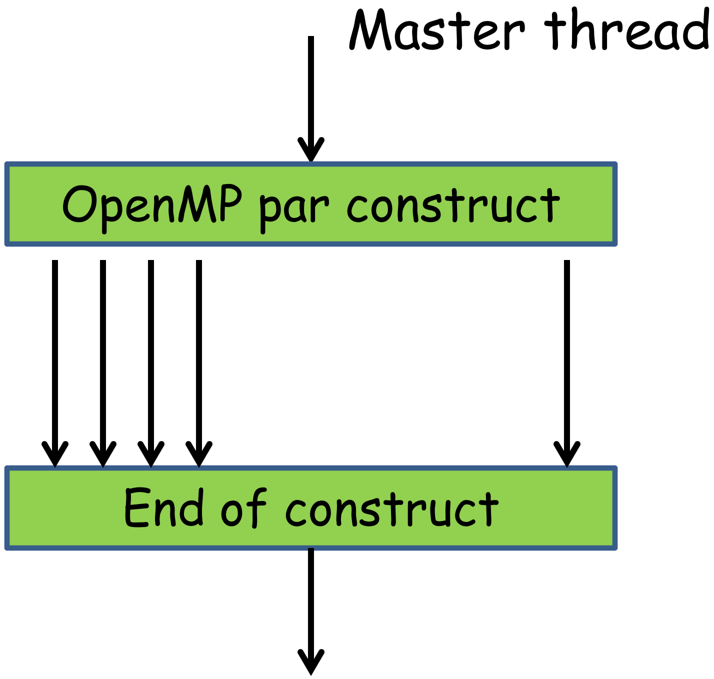
Just setting shared variable threads to at most max_threads

```
int main(int argc, char *argv[]){
   int threads, myid;
  int i;  threads = 1;

// …

#pragma omp parallel num_threads(threads)
  {
    myid = omp_get_thread_num();
    printf("Thread %d of %d active\n",myid,threads);
  }

  return 0;
}
```

OpenMP directive: parallel region executed by num_threads cores

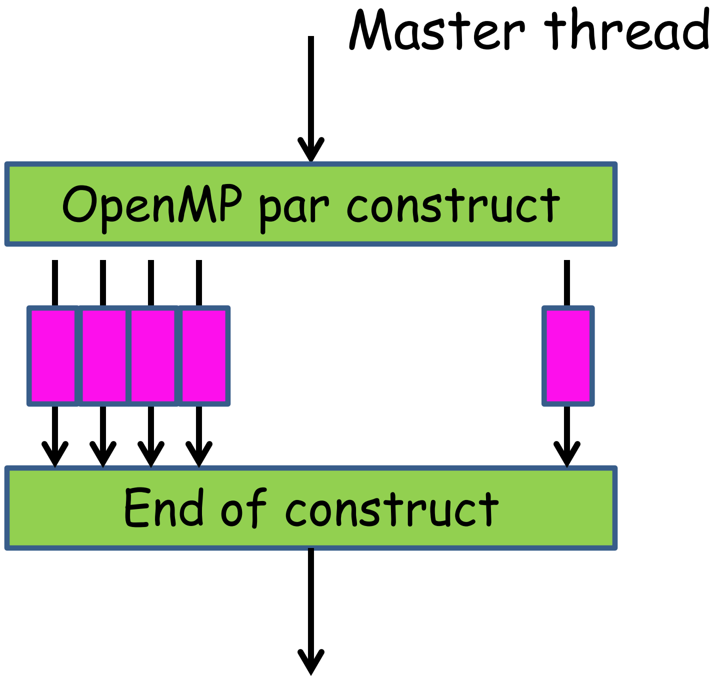
Library call: get thread id – should rarely be needed

Basic work sharing constructs



```
#pragma omp parallel
{
   // threads
}
```

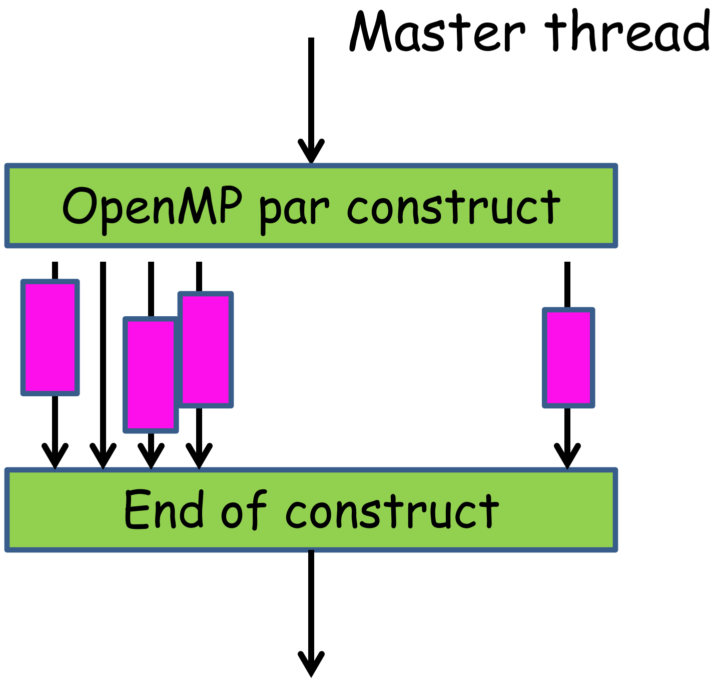
Basic work sharing constructs



```
#pragma omp parallel
{
  #pragma omp for
  for (i=0; i<n; i++) {
    // iterations shared
  }
}
```

Data parallel loop scheduled over available threads

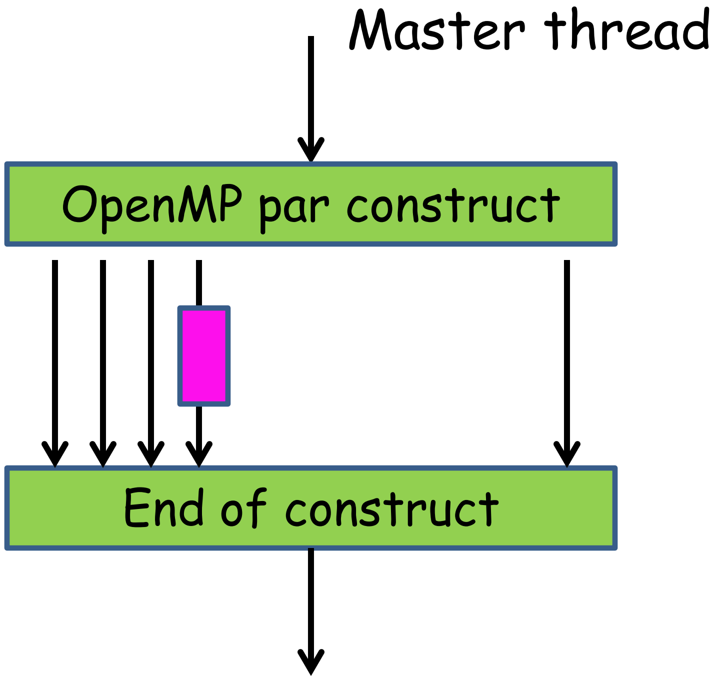
Basic work sharing constructs



Static, finite task parallelism

```
#pragma omp parallel
{
  #pragma omp sections
  #pragma omp section
  {
    // A
  }
  #pragma omp section
  {
     // B
  }
  // …
}
```

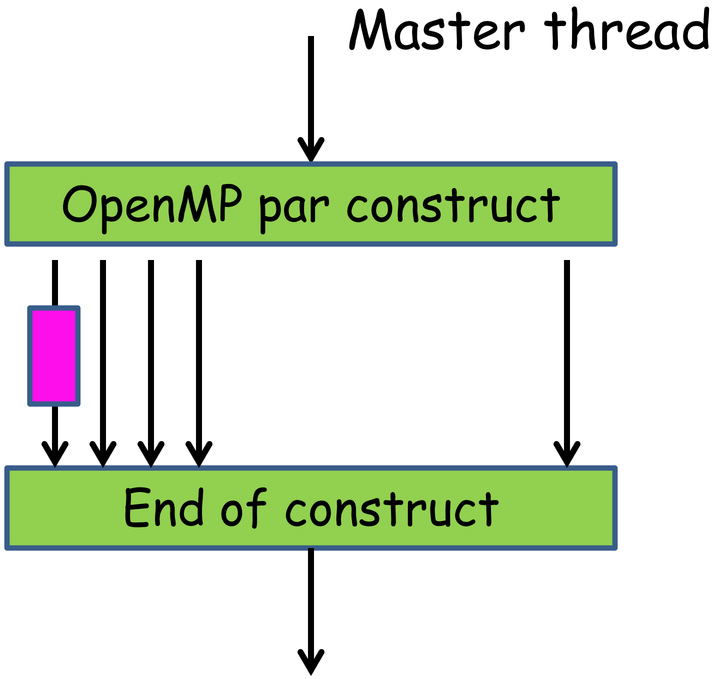
Basic work sharing constructs



```
#pragma omp parallel
{
  #pragma omp single
  {
    // some thread
  }
}
```

Sequential code in parallel construct, no mutual exclusion

Basic work sharing constructs



```
#pragma omp parallel
{
  #pragma omp master
  {
    // master thread 0
  }
}
```

Sequential code by master in parallel construct, no mutual exclusion

The parallel construct

```
#pragma omp parallel [clause ...]
<structured block>
```

Starts an explicit parallel section/block/region with default number of threads

Example, explicit parallelization of loop of independent iterations

```
for (i=0; i<n; i++) {
  a[i] = f(i);
}
```

```
#pragma omp parallel
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

  for (i=start; i<end; i++) {
    a[i] = f(i);
  }
}
```

Local variables, per thread

Implicit barrier, all threads have completed their loop, back to master thread, all iterations have been completed

```
#pragma omp parallel
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

  for (i=start; i<end; i++) {
    a[i] = f(i);
  }
}
```

Note:

Not allowed to jump into or break out of parallel region (same for the work sharing and other OpenMP constructs).

```
#pragma omp parallel
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

  for (i=start; i<end; i++)
    a[i] = f(i);
  }
}
```

OpenMP library calls

Default number of threads determined by

1. Environment (run command), can be changed by environment variable `OMP_NUM_THREADS`, e.g

```
setenv OMP_NUM_THREADS 5
```

2. Explicit setting in program by library call
`omp_set_num_threads(t);`

3. Clause `num_threads(t)` in `#pragma omp parallel` construct

Note: 3 overrides 2; 2 overrides 1

Library functions for (explicit) thread access

```
#include <omp.h>

void omp_set_num_threads(int num_threads);
int omp_get_num_threads(void);

int omp_get_max_threads(void);

int omp_get_thread_num(void);

int omp_get_num_procs(void);
```

Threads in parallel region are numbered successively from `0` to `omp_get_num_threads()-1`

Master thread has number `0`

Library functions for (explicit) thread access

```
#include <omp.h>

void omp_set_num_threads(int num_threads);
int omp_get_num_threads(void);

int omp_get_max_threads(void);

int omp_get_thread_num(void);

int omp_get_num_procs(void);
```

Number of default threads for OpenMP regions can be set by `omp_set_num_threads(t)`. Maximum number of threads allowed by system is `omp_get_max_threads();`

```
#pragma omp parallel if (n<1000) num_threads(4)
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

  for (i=start; i<end; i++) {
    a[i] = f(i);
  }
}
```

Fixing number of threads for region

Conditional clause, scalar expression evaluated at runtime

Variables declared before parallel region are per default shared for all threads

```
int *a;
a = (int*)malloc(n*sizeof(a*));

#pragma omp parallel
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

  for (i=start; i<end; i++) {
    a[i] = f(i);
  }
}
```

Will be shared

Local variables, per thread

Sharing can be controlled at entry to parallel region

- Clause `shared(<list of vars>)`
- Clause `private(<list of vars>)`
- Clause `firstprivate(<list of vars>)`
- Clause `lastprivate(<list of vars>)`

- Clauses `default(shared)`, `default(none)`

For variables declared as private, a local copy per thread is created. With `private`: not initialized, with `firstprivate` initalized to value in master thread prior to parallel section; `lastprivate` copies value from „last" thread back

Variables declared before parallel region are per default shared for all threads

```
int *a;
a = (int*)malloc(n*sizeof(a*));

#pragma omp parallel private(a)
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

  for (i=start; i<end; i++) {
    a[i] = f(i);
  }
}
```

Pointer is private

Variables declared before parallel region are per default shared for all threads

```
int a[200]

#pragma omp parallel private(a)
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

  for (i=start; i<end; i++) {
    a[i] = f(i);
  }
}
```

Pointer and array content private??

Good practice(?): disable default rule, explicit sharing declaration for all variables in enclosing scope

```
int *a;
a = (int*)malloc(n*sizeof(a*));

#pragma omp parallel default(none) \
private(a)
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

  for (i=start; i<end; i++) {
    a[i] = f(i);
  }
}
```

C preprocessor line continuation

Pointer is private

Summary of clauses for `#pragma omp parallel`

```
if (scalar_expression)
private (list)
shared (list)
default (shared | none)
firstprivate (list)
reduction (operator: list)
copyin (list)
num_threads (integer-expression)
```

See later for reduction clause…

Work sharing constructs: loop, sections, single/master

OpenMP constructs for assignment of threads to statements/blocks of code

Instead explicit, and possibly inefficient assignment/scheduling

```
#pragma omp parallel
if (omp_get_thread_num()==0) {
  // do that
} else if (omp_get_thread_num==1) {
  // do this
} else …
```

OpenMP provides implicit means of assigning work to threads

Parallel sections

```
#pragma omp sections [clause ...]
{
#pragma omp section
  taskA(…);
#pragma omp section
{
  // explicit block of code for some task
}
#pragma omp section
…
}
```

More threads than tasks: some threads idle

Discrete, fixed number of tasks will be assigned to active threads

Parallel sections

```
#pragma omp sections [clause ...]
{
#pragma omp section
  taskA(…);
#pragma omp section
{
  // explicit block of code for some task
}
#pragma omp section
…
}
```

More tasks than threads: Some threads execute more than one task, scheduling implementation dependent

Discrete, fixed number of tasks will be assigned to active threads

Example: loop with two independent operations

```
int i;
float a[N], b[N], c[N], d[N];

for (i=0; i < N; i++) {
  a[i] = …;
  b[i] = …;
}

for (i=0; i < N; i++) {
  c[i] = a[i] + b[i];
  d[i] = a[i] * b[i];
}
```

```
int i;
float a[N], b[N], c[N], d[N];
for (i=0; i < N; i++) {
  a[i] = …;
  b[i] = …;
}

#pragma omp parallel deafult(none) \
shared(a,b,c,d) private(i)
{
  #pragma omp sections nowait
  {
    #pragma omp section
    for (i=0; i < N; i++) c[i] = a[i] + b[i];   „Task 1“
    #pragma omp section
    for (i=0; i < N; i++) d[i] = a[i] * b[i];   „Task 2“
  } /* end of sections */
} /* end of parallel section */
```

Summary of clauses for `#pragma omp sections`

```
private (list)
firstprivate (list)
lastprivate (list)
reduction (operator: list)
nowait
```

For reduction and nowait, see later…

Single construct, master construct

Block inside parallel region that is to be executed by only one thread, either arbitrarily, or by master thread (Master: `omp_get_thread_num()==0`)

```
#pragma omp single [clause]
```

Some – but only one - thread executes block, implicit barrier after block

```
#pragma omp master
```

Master thread executes block, no barrier

```
#pragma omp parallel
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

#pragma omp single
  readarray(b,n);

  for (i=start; i<end; i++) {
    a[i] = b[i];
  }

#pragma omp single
  printf(„now done?“);
}
```

Implicit barrier, all threads will see their part of the array

Dangerous: No barrier before `single`

```
#pragma omp parallel
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

#pragma omp master
  readarray(b,n);

  for (i=start; i<end; i++) {
    a[i] = b[i];
  }

#pragma omp barrier
#pragma omp single
  writearray(a,n); // all updates done!
}
```

Master thread reads; dangerous because no barrier

Explicit barrier,

Implicit barrier here

```
#pragma omp parallel
{
  int i;
  int block = n/omp_get_num_threads();
  int start = omp_get_thread_num()*block;
  int end = start+block;

#pragma omp single
  readarray(b,n);

  for (i=start; i<end; i++) {
    a[i] = b[i];
  }

#pragma omp barrier
#pragma omp single nowait
  printf(„now done?“);
}
```

Eliminate implicit barrier

Implicit barrier here

Summary of clauses for `#pragma omp single`

```
private (list)
firstprivate (list)
nowait
```

`nowait`: implicit barrier synchronization at end of construct will not take place

Also: `sections`, `for` constructs. Not: `parallel`

Use with care for performance tuning

Parallel for

Basic work sharing construct – iterations of a loop distributed among default available threads

```
#pragma omp for [clause]
```

Example: loop parallelization

```
for (i=0; i<n; i++) {
  a[i] = f(i);
}
```

```
#pragma omp parallel
{
  int i;

#pragma omp for
  for (i=0; i<n; i++) {
    a[i] = f(i);
  }
}
```

Iteration variable per default private

Loop iterations divided according to default schedule across threads

Basic rule: total number of iterations must be known before loop, all threads must compute same iterations bound

Parallel loop shorthand

```
int i;

#pragma omp parallel for
for (i=0; i<n; i++) {
    a[i] = f(i);
}
```

- Implicit barrier after loop
- No break, or jump into/out of loop

Illegal

```
#pragma omp parallel for
for (;;) {
  // C open loop
}
```

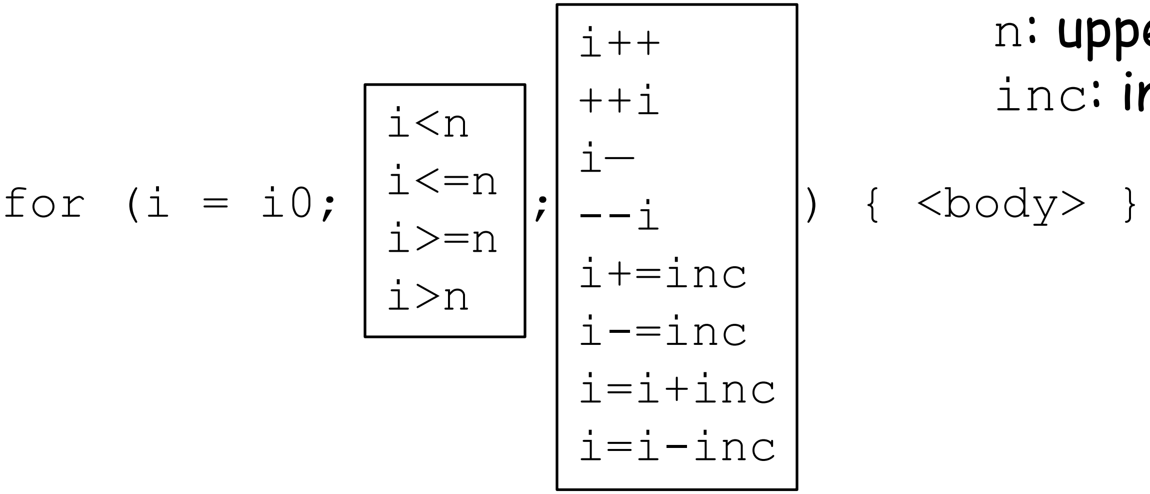
Number of iterations unknown, not in canonical form

```
#pragma omp parallel for
for (i=0; i<n; i++) {
  if (exceptional(i)) break;
  if (i%2==0) continue;
}
```

Break out of loop. Continue ok, does not change number of iterations

OpenMP compiler may complain

For loops must be in canonical form



```
                  i<n       i++
                  i<=n      ++i
                  i>=n      i–
for (i = i0;      i>n   ;   --i        ) { <body> }
                            i+=inc
                            i-=inc
                            i=i+inc
                            i=i-inc
```

`i`: iteration variable
`i0`: lower bound
`n`: upper bound
`inc`: incement

- •No `break`, `goto` out of loop body; `continue` allowed
- •Lower, upper, increment expressions must not change during loop iterations

Also illegal

```
#pragma omp parallel for
for (i=0; i<n; i*=2) {
  a[i] = …;
}
```

Number of iterations known, but not in canonical form

Parallel for schedules

p: number of threads, n number of iterations

- Per default, iteration space divided into blocks of approx. n/p iterations, one block is assigned to each thread. Blocks of iterations: chunks in OpenMP
- Schedule, assignment to threads, can be changed by `schedule` clause
- Chosen schedule can have a huge effect on performance (false sharing, e.g.)

Schedule clause, chunksize optional

- `schedule(static,<chunksize>)`: iterations divided into chunks of size (default approx. n/p), chunks assigned to threads in a round robin fashion

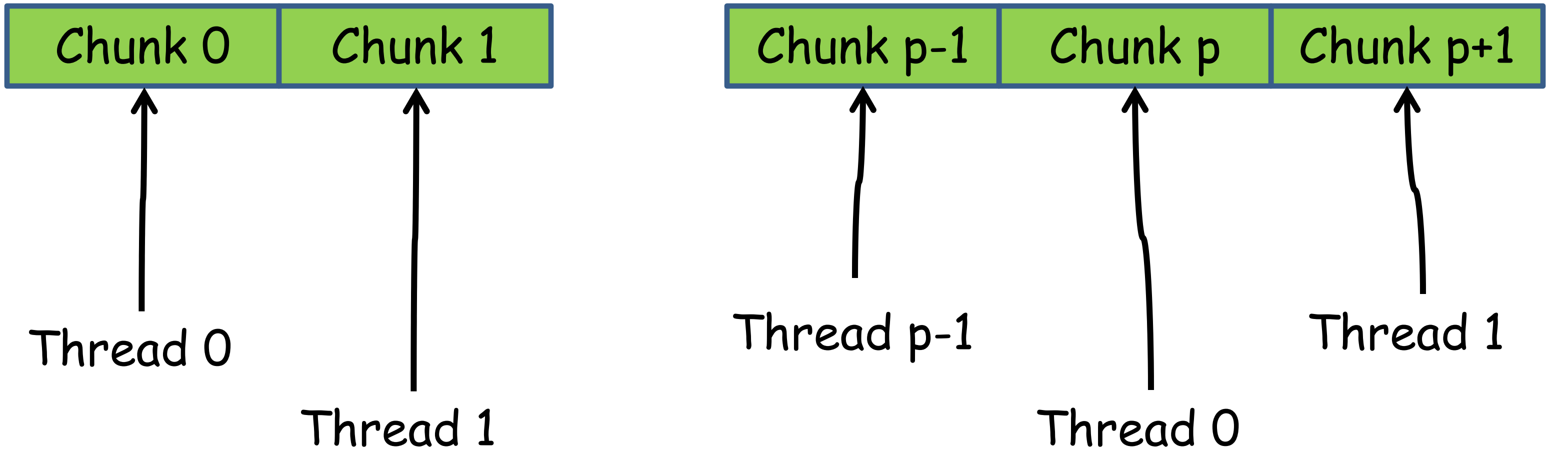
- `schedule(dynamic,<chunksize)`: chunks are distributed to threads as threads become free and request work (default chunksize 1)

- `schedule(guided,<chunksize>)`: as dynamic, but chunksize is adjusted downwards to the number of unassigned iterations divided by p (default chunksize 1)

- `schedule(auto)`: schedule is determined by compiler or runtime

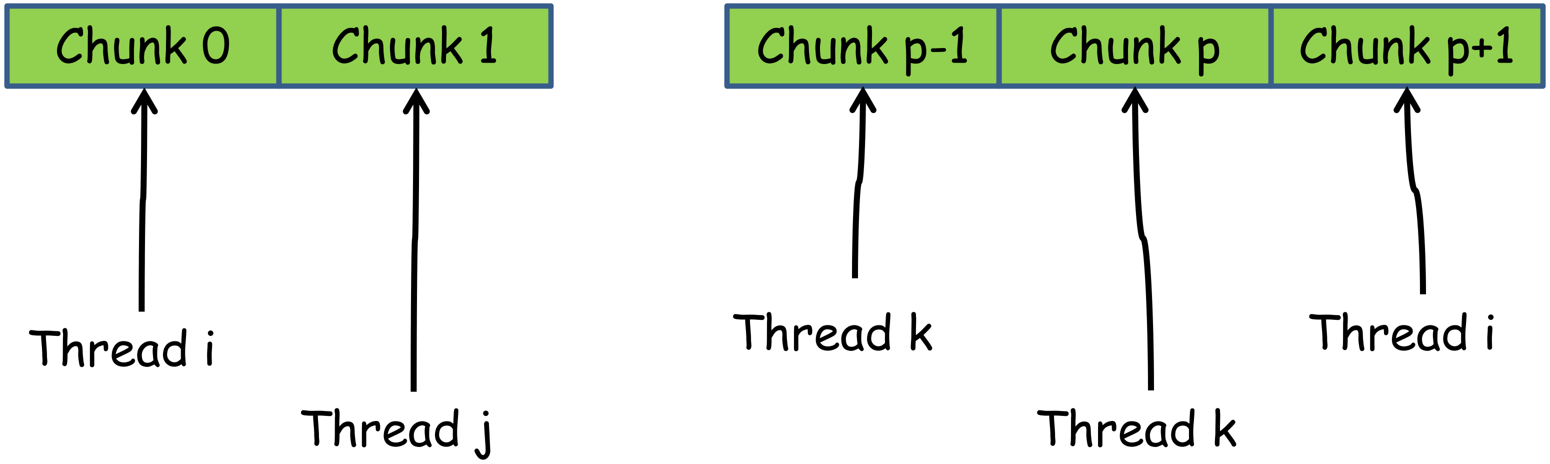
- `schedule(runtime)`: schedule left to runtime & environment

```
schedule(static,<chunksize>)
```



Chunks executed in order in parallel, thread i executes chunk i%p

```
schedule(dynamic,<chunksize>)
```



Chunks executed in order, each thread executes some chunk, thread i executes next available chunk

Work-pool like: `chunk = fetch_and_add(&i,chunksize);`

With `runtime` scheduling schedule can be set by environment variable, e.g.

```
setenv OMP_SCHEDULE „guided“
setenv OMP_SCHEDULE „dynamic, 4“
setenv OMP_SCHEDULE „static, 100“
```

Note: number of threads allocated for parallel construct may be set/adjusted at runtime – dynamic threads

```
#define OMP_DYNAMIC true/false
```

```
#include <omp.h>

void omp_set_dynamic(int dynamic_threads)
int omp_get_dynamic(void)
```

Example: matrix-vector

y= x*A, nxm matrix x, m vector A

```
#pragma parallel for
for (i=0; i<n; i++) {
  y[i] = 0;
  for (j=0;j<m; j++) {
    y[i] += x[i][j]*A[j];
  }
}
```

Default:
each thread performs
n/p successive
iterations of inner loop

Example: matrix-vector

y= x*A, nxm matrix x, m vector A

```
#pragma parallel for schedule(static)
for (i=0; i<n; i++) {
  y[i] = 0;
  for (j=0;j<m; j++) {
    y[i] += x[i][j]*A[j];
  }
}
```

As default: each thread performs n/p successive iterations of inner loop

Example: matrix-vector

y= x*A, nxm matrix x, m vector A

```
#pragma parallel for schedule(static,1)
for (i=0; i<n; i++) {
  y[i] = 0;
  for (j=0;j<m; j++) {
    y[i] += x[i][j]*A[j];
  }
}
```

Chunks of single iteration. Probably causes false sharing

To experiment with best schedule, e.g. use `runtime` and set actual schedule by environment variable

Summary of clauses for `#pragma omp for`

```
schedule (type [,chunk])
ordered
private (list)
firstprivate (list)
lastprivate (list)
shared (list)
reduction (operator: list)
collapse (n)
nowait
```

Reduction, see later…

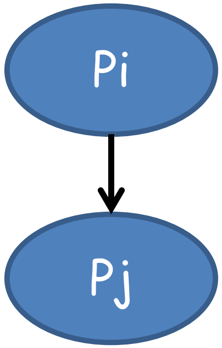
Correctness, independence

OpenMP principle:
Parallel regions and all work sharing constructs assume that code regions executed by threads can be safely executed in parallel

Code region executions must be independent: no update to a shared variable in one region can have an effect on other region

OpenMP principle:
It is the programmers responsibility to ensure independence. Compiler & runtime are not required to check, will not do

Pi program fragment followed by program fragment Pj; sequentially Pj executed after Pj



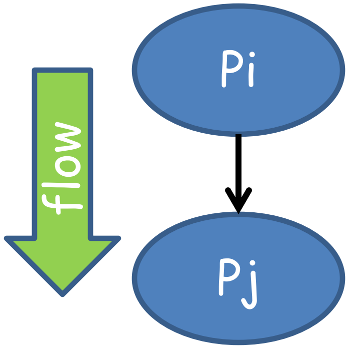
I: variables read in P (input)
O: variables written in P (output)

The two fragments are independent and can be executed in parallel if

1. Oi intersection Ij = Ø
2. Ii intesection Oj = Ø
3. Oi intersection Oj= Ø

„Bernstein's conditions"

[A. J. Bernstein: "Program Analysis for Parallel Processing". IEEE Trans. on Electronic Computers. EC-15, pp. 757–62, 1966]

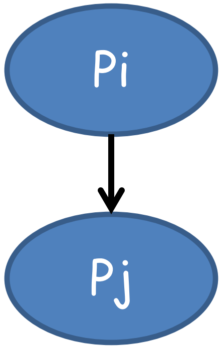


1. Oi intersection Ij ≠ Ø

Pi writes to a variable that is read by Pj

Flow dependency, true dependency

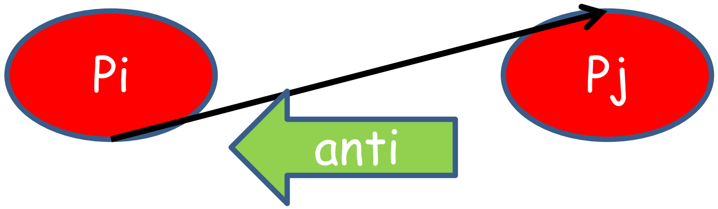
Pi must be executed before Pj



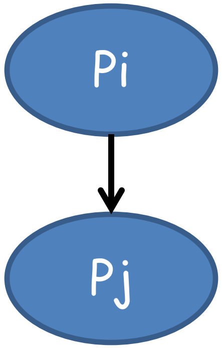
2. Oj intersection Ii ≠ Ø

Pj writes to a variable that was read by Pi

Anti dependency



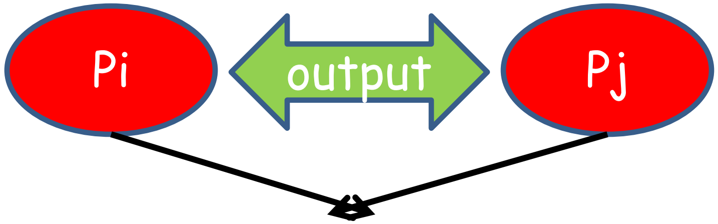
Pj cannot be executed before/concurrently with Pi



3. Oi intersection Oj ≠ Ø

Pi and Pj writes to the same variable

Output dependency



Becomes race condition if Pi and Pj are executed in different order/concurrently

Loop carried flow dependency, if k>0

```
for (i=k; i<n; i++) a[i] = a[i-k]+a[i];
```

Dependency is between different iterations of loop, sequentially later iteration i+k depends on output of iteration i

Loop carried anti-dependency

```
for (i=0; i<n-k; i++) a[i] = a[i]+a[i+k];
```

Loop carried output dependency, if more than one prime before n

```
for (i=1; i<n; i++) if (isprime(i))
a[0] = a[i];
```

Simple rule of thumb for OpenMP parallelizable loops

1. Array updates only
2. Each array element updated in at most one iteration
3. No iteration reads element assigned by another iteration

Dependencies within same iteration allowed

```
for (i=0; i<n; i++) {
  a[i] = f(i);
  b[i] = g(i);
  c[i] = a[i]+b[i];
}
```

```
#pragma omp parallel for
for (i=0; i<n; i++) {
  a[i] = f(i);
  b[i] = g(i);
  c[i] = a[i]+b[i];
}
```

Or

```
#pragma omp parallel for
for (i=0; i<n; i++) a[i] = f(i);
#pragma omp parallel for
for (i=0; i<n; i++) b[i] = g(i);
#pragma omp parallel for
for (i=0; i<n; i++) c[i] = a[i]+b[i];
```

Implicit barrier

Probably inefficient, better

```
#pragma omp parallel for nowait
for (i=0; i<n; i++) a[i] = f(i);
#pragma omp parallel for
for (i=0; i<n; i++) b[i] = g(i);
#pragma omp parallel for
for (i=0; i<n; i++) c[i] = a[i]+b[i];
```

No barrier after for; ok since no dependency on a in next loop

Barrier needed

Some loop carried dependencies

```
for (i=k; i<n; i++) a[i] = a[i]+a[i+k];
```

can be eleminated with temporary variables

```
for (i=k; i<n; i++) aa[i] = a[i]+a[i+k];
// swap
tmp = a; a = aa; aa = tmp;
```

`aa` temporary (extra) array – not only pointer! No loop-carried dependencies

Thus

```
#pragma omp parallel for firstprivate(k)
for (i=k; i<n; i++) aa[i] = a[i]+a[i+k];
// swap
tmp = a; a = aa; aa = tmp;
```

Standard example: solving Poisson equation, loop

$$u[i][j] <- \tfrac{1}{4}(u[i][j-1]+u[i][j+1]+u[i-1][j]+u[u+1][j]-h\hat{}2*f(i,j))$$

```
#pragma omp parallel for
for (i=1; i<n-1; i++) {
  for (j=1; j<n; j++) {
    unext[i][j] = 0.25*(u[i][j-1]+u[i][j+1]+…);
  }
}
uu = u; u = unext; unext = uu; // swap
```

Needs allocation of full temporary matrix, space O(n^2).

Copy back may be needed if result of last iteration is in the temporary array

Parallel prefix-sums computation (1st loop)

```
for (k=1; k<n; k=kk) {
  kk = k<<1; // double
  for (i=kk-1; i<n, i+=kk) {
    x[i] = x[i-k]+x[i];
  }
  barrier;
}
```

No loop carried dependency; x[i] are every kk'th element and only updated, not read in other iteration

```
for (k=1; k<n; k=kk) {
  kk = k<<1; // double
#pragma omp parallel for
  for (i=kk-1; i<n, i+=kk) {
    x[i] = x[i-k]+x[i];
  }
}
```

Implicit barrier after parallel for region

Some dependencies cannot be resolved easily, require different approach

```
for (i=k; i<n; i++) a[i] = a[i-1]+a[i];
```

Sequential computation of all inclusive prefix sums. Parallel algorithms solve problem work-optimally in O(n/p+log p)

No explicit support in OpenMP

Some dependencies cannot be resolved easily, require different approach

```
for (i=k; i<n; i++) a[i] = a[i-1]+a[i];
```

Sequential computation of all inclusive prefix sums. Parallel algorithms solve problem work-optimally in O(n/p+log p)

No explicit support in OpenMP

Different from

```
for (i=k; i<n; i++) sum = sum+a[i];
```

Reduction pattern, can be handled by OpenMP compiler & runtime

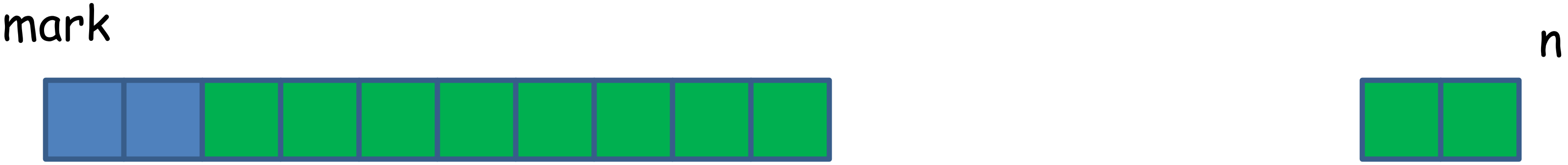
Example: Erathostenes prime sieve

```
for (i=2; i<n; i++) mark[i] = 1;

k = 0;
for (i=2; i*i<n; i++) {
  if (mark[i]) prime[k++] = i;
  for (j=i*i; j<n; j+=i) mark[j] = 0;
}

for (; i<n; i++) if (mark[i]) prime[k++] = i;
```

Finds all primes up to n by crossing out multiples of each newly found prime. Task is to return the found primes in increasing order in array `prime`

Note: by addition only

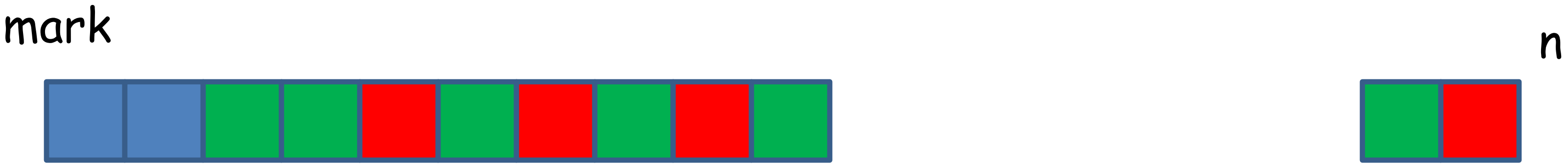
mark
n



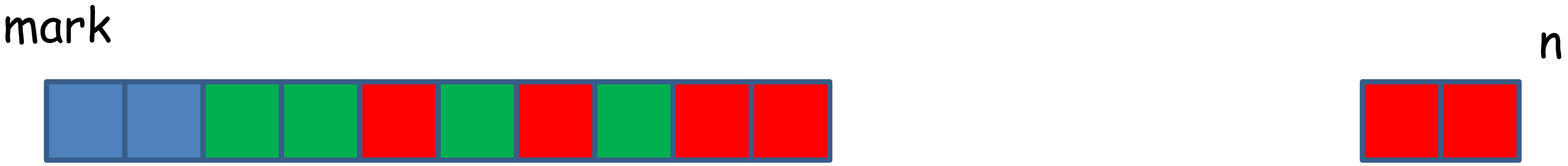
```
for (i=2; i<n; i++) mark[i] = 1;
```

Initialize mark array

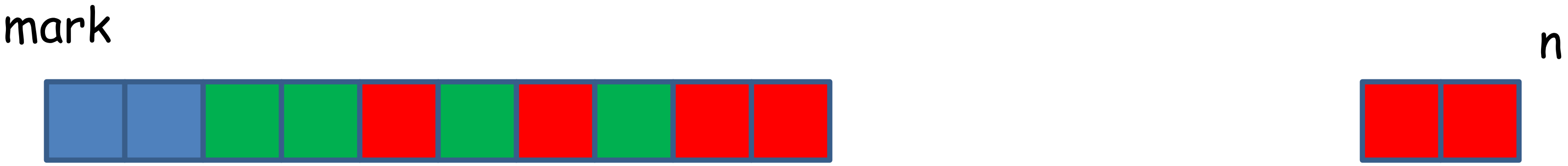
Implementation: bit array, only odd numbers, etc.



i==2:
mark[i] true, so prime, unmark multiples

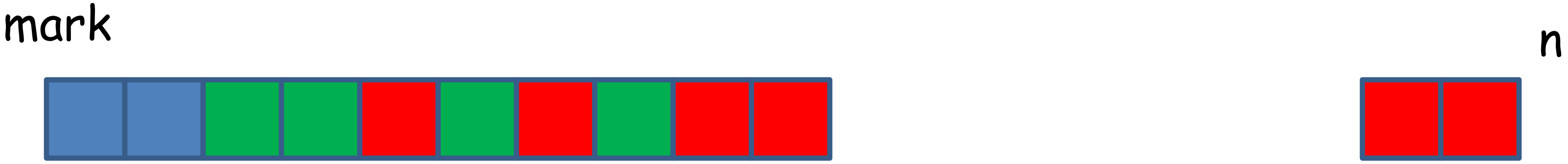


i==3:
mark[i] true, so prime, unmark multiples



i==4:

mark[i] false, not prime, continue



i==5:
mark[i] true, so prime, unmark multiples

Etc, until √n

```
for (i=2; i<n; i++) mark[i] = 1;

k = 0;
for (i=2; i*i<n; i++) {
  if (mark[i]) prime[k++] = i;
  for (j=i*i; j<n; j+=i) mark[j] = 0;
}

for (; i<n; i++) if (mark[i]) prime[k++] = i;
```

Need only to eliminate multiples up to √n

All multiples less than i^2 have been eliminated

Lemma: This Sieve-of-Erathostenes finds all primes from 2 to n in O(n √n), actually O(n log log n)

„Proof“:

- Correctness:

If $p*q = x$ then either $p \le \sqrt{n}$ or $q \le \sqrt{n}$

Invariant: before iteration i, all multiples of $j<i$ have been crossed out. Therefore, when i is found marked (therefore prime), $2*i$, $3*i$, $4*i$, … $(i-1)*i$ and multiples have been eliminated. It suffices to cross out from $i*i$

- Time:

By prime number theorem etc. $\sum p\ \text{prime}\le n: n/p = n \ln \ln n$

Note: exponential in size of n which is O(log n), pseudopolynomial

```
#pragma omp parallel for
for (i=2; i<n; i++) mark[i] = 1;

k = 0;
for (i=2; i*i<n; i++) {
  if (mark[i]) prime[k++] = i;
#pragma omp parallel for
  for (j=i*i; j<n; j+=i) mark[j] = 0;
}

#pragma omp parallel for
for (; i<n; i++) if (mark[i]) prime[k++] = i;
```

Inner loop can be parallelized

Not in canonical form

Loop-carried dependencies

Solution 1: enforce sequential order

```
#pragma omp parallel for
for (i=2; i<n; i++) mark[i] = 1;

k = 0;
for (i=2; i*i<n; i++) {
  if (mark[i]) prime[k++] = i;
#pragma omp parallel for
  for (j=i*i; j<n; j+=i) mark[j] = 0;
}
int ii = i;
#pragma omp parallel for ordered
for (i=ii; i<n; i++) if (mark[i]) {
#pragma omp ordered
  prime[k++] = i;
}
```

Why necessary?

Sequential order will be enforced for ordered region `ordered` clause in parallel for region enforces same order of iterations for the ordered region

Ordered region `#pragma omp ordered`

Only one ordered region in parallel ordered for loop. Many restrictions

Parallelization by OpenMP system hardly done, can lead to slowdown

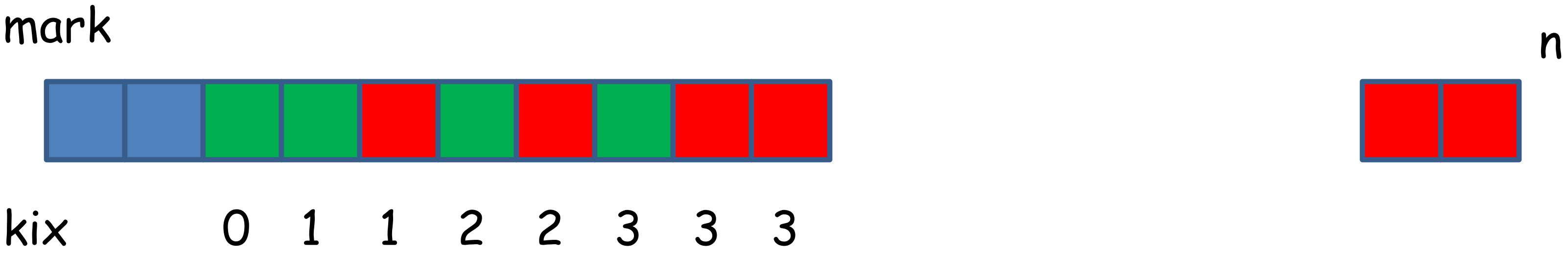
Solution 2: index computation in parallel

```
#pragma omp parallel for
for (i=2; i<n; i++) mark[i] = 1;

k = 0;
for (i=2; i*i<n; i++) {
  if (mark[i]) prime[k++] = i;
#pragma omp parallel for
  for (j=i*i; j<n; j+=i) mark[j] = 0;
}
int ii = i;
#pragma omp parallel for
for (i=ii; i<n; i++) kix[i] = (mark[i]) ? 1 : 0;
Exscan(kix+m,n-m); // all prefix-sums
#pragma omp parallel for
for (i=m; i<n; i++) if (mark[i]) prime[k+kix[i]] = i;
```

Solution 2: index computation in parallel

```
#pragma omp parallel for
for (i=2; i<n; i++) mark[i] = 1;

k = 0;
for (i=2; i*i<n; i++) {
  if (mark[i]) prime[k++] = i;
#pragma omp parallel for
  for (j=i*i; j<n; j+=i) mark[j] = 0;
}
int ii = i;
#pragma omp parallel for
for (i=ii; i<n; i++) kix[i] = (mark[i]) ? 1 : 0;
Exscan(kix+m,n-m); // all prefix-sums
#pragma omp parallel for
for (i=m; i<n; i++) if (mark[i]) prime[k+kix[i]] = i;
```

Indexing marked elements by exclusive scan



mark

n

kix 0 1 1 2 2 3 3 3

Solution 2: index computation in parallel

Bonus exercise: Use parallel-prefix implementation, see if better performance can be achieved than with ordered

```
#pragma omp parallel for
for (i=2; i<n; i++) mark[i] = 1;

k = 0;
for (i=2; i*i<n; i++) {
  if (mark[i]) prime[k++] = i;
#pragma omp parallel for
  for (j=i*i; j<n; j+=i) mark[j] = 0;
}
int ii = i;
#pragma omp parallel for
for (i=ii; i<n; i++) kix[i] = (mark[i]) ? 1 : 0;
Exscan(kix+m,n-m); // all prefix-sums
#pragma omp parallel for
for (i=m; i<n; i++) if (mark[i]) prime[k+kix[i]] = i;
```

Parallel work-time:

$O(n \log\log n/p + \sqrt{n})$

Inner loop and last loop parallelized, number of (sequential) iterations of outer loop $\sqrt{n}$

Reductions

```
sum = 0;
for (i=0; i<n; i++) sum += i;
```

Standard operation with flow and output dependencies

```
sum = 0;
for (i=0; i<n; i++) sum += expr(a[i]);
```

Such patterns can be recognized by OpenMP compiler, and efficient algorithm/runtime support used

```
sum = 0;
#pragma omp parallel reduction(+,sum)
for (i=0; i<n; i++) sum += i;
```

`reduction(<operator>,<variable list>)` clause specifies reduction with operator on list of variables

Operator: `+, *,-,&,|,^,&&,||` and min/max computations

More reductions

```
int i, b, c;
float a, d;
a = 0.0;
b = 0;
c = y[0];
d = x[0];
#pragma omp parallel for private(i) shared(x, y, n) \
reduction(+:a) reduction(^:b) \
reduction(min:c) reduction(max:d)
for (i=0; i<n; i++) {
  a += x[i];
  b ^= y[i];
  if (c > y[i]) c = y[i];
  d = fmaxf(d,x[i]);
}
```

Two different min/max expressions

Parallel region with worksharing constructs and reduction

```
#pragma omp parallel shared(a) private(i)
{
#pragma omp master
a = 0;
// To avoid race condition, barrier here
#pragma omp barrier

#pragma omp for reduction(+:a)
for (i = 0; i < 10; i++) {
a += i;
}
#pragma omp single
printf ("Sum is %d\n", a);
}
```

Critical sections, atomic operations

(named) critical section. In parallel region, enforces mutual exclusion of thread code region

```
#pragma omp critical [(<name>)]
```

Critical sections are statically designated (compile time)

```
int t;

#pragma omp parallel
{
  t = omp_get_thread_num();
  print(„Thread id is %d\n“,t);
}
```

Race condition because of shared t

```
int t;

#pragma omp parallel
{
#pragma omp critical
  {
    t = omp_get_thread_num();
    print(„Thread id is %d\n“,t);
  }
}
```

Now in critical section, mutual exclusion (update of shared t) guaranteed

```
#pragma omp atomic read
pvar = svar; // read shared variable atomically
```

```
#pragma omp atomic write
svar = pvar; // write to shared variable atomically
```

```
#pragma omp atomic update
<expression statement>
```

Expression-statement can be

```
x++;
x--;
++x;
--x;
x op= expr;
x = x op expr;
```

```
op:
+, *, -, /, &,
^, |, <<, >>
```

Locks for mutual exclusion created dynamically

```
#include <omp.h>

void omp_init_lock(omp_lock_t *lock);
void omp_init_nest_lock(omp_nest_lock_t *lock);

void omp_destroy_lock(omp_lock_t *lock);
void omp_destroy_nest_lock(omp_nest_lock_t *lock);
```

Must be allocated/initialized, and destroyed again

No fairness guarantee

```
#include <omp.h>

void omp_set_lock(omp_lock_t *lock);
void omp_set_nest__lock(omp_nest_lock_t *lock);

void omp_unset_lock(omp_lock_t *lock);
void omp_unset_nest_lock(omp_nest_lock_t *lock);

int omp_test_lock(omp_lock_t *lock);
int omp_test_nest_lock(omp_nest_lock_t *lock);
```

Summary: Five ways of handling simple reduction

```
for (i=k; i<n; i++) sum = sum+a[i];
```

Canonical way, best potential for good performance: `reduction` clause

```
#pragma omp parallel for reduction(+,sum)
for (i=k; i<n; i++) sum = sum+a[i];
```

Project/exercise: compare this to hand-written prefix algorithm

Sequential thinking, enforce sequential order with `ordered` clause

```
#pragma omp parallel for ordered
for (i=k; i<n; i++) {
#pragma omp ordered
  sum = sum+a[i];
}
```

Performance pitfall: probably close to sequential loop (plus overhead?)

Concurrent thinking: Critical section

```
#pragma omp parallel for
for (i=k; i<n; i++) {
#prgama omp critical
  sum = sum+a[i];
}
```

Might perform reasonably if much other work in parallel region for the threads, but probably not

Correct only if operator + is commutative!

Variant: use locks, same problems

Delegate to hardware: atomic operations

```
#pragma omp parallel for
for (i=k; i<n; i++) {
#pragma omp atomic
  sum = sum+a[i];
}
```

Timing OpenMP computations for performance eavluation

Wall clock time in OpenMP

```
#include <omp.h>

double omp_get_wtime(void);
double omp_get_wtick(void);
```

Wall-clock time in seconds since some time in the past returned

Discussion, not covered

Easy to use, but limited language addition for parallel thread programming: data parallel loops, access to possibly hardware-supported atomic operations, plus some-level concurrent programming like primitives

Stepwise parallelization idea?? Program structure will need change (e.g. canonical loops, dependency elimination)

Discussion, not covered

Not covered:

- Nesting: work-sharing constructs can be nested, but are executed by single thread only, unless OpenMP 3.0 nesting is supported
- Task construct, OpenMP 3.0
- Memory flushing, `#pragma omp flush`
- A few other things…