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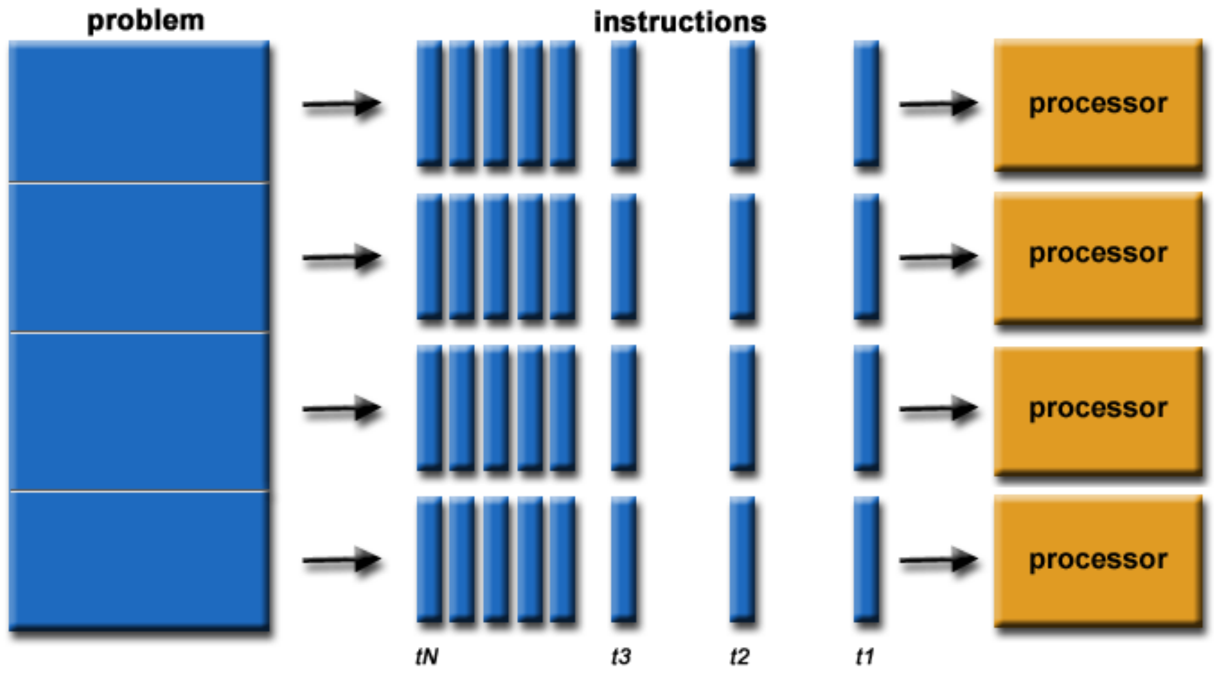
# Parallel Programming

Presented by CSCNSI

## Working in parallel

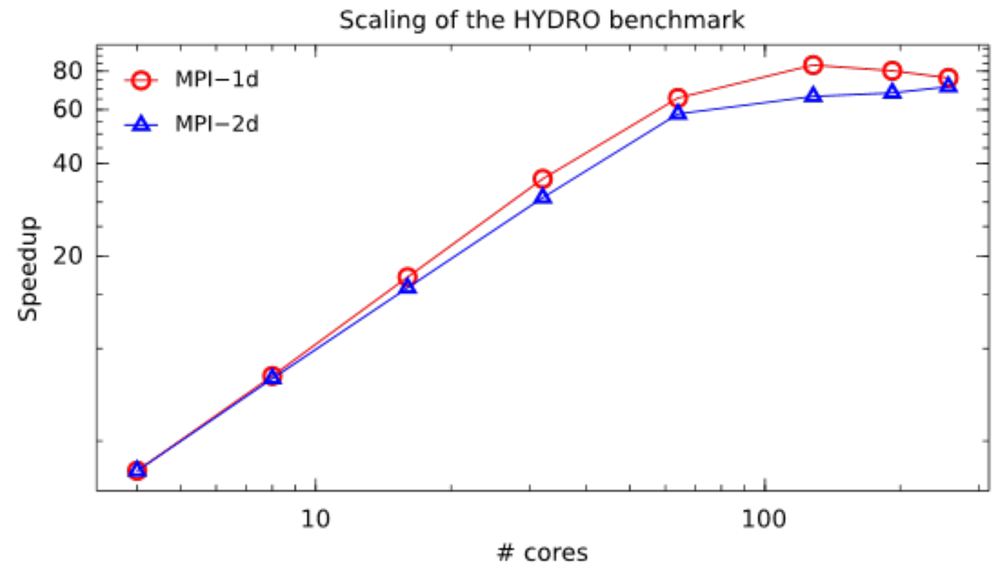
- Processors aren’t getting faster
- But we are getting more of them
- We have to find ways to work in parallel
  - Performance tuning = parallelization
- Modern optimization is largely the process of making algorithms more parallel

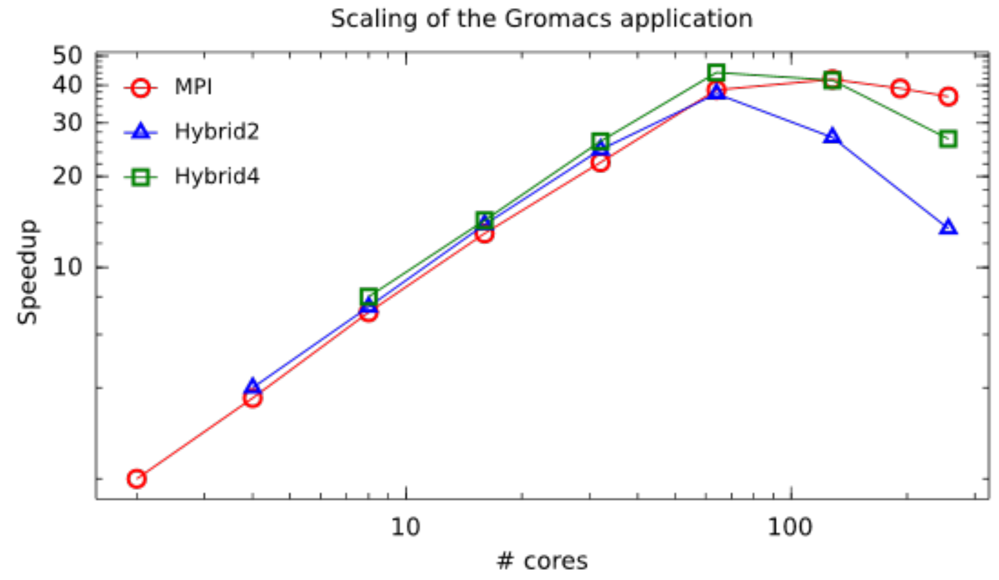


https://computing.llnl.gov/tutorials/parallel_comp/

## Parallel Scaling

- Scaling is hard
- Usually we reach a plateau
- Things that can get us over the plateau (roughly in order of efficacy)
  - Rethinking our algorithms
    - Sometimes requires rethinking scientific approximations
  - Writing better parallelism
  - Improving hardware level paralellism

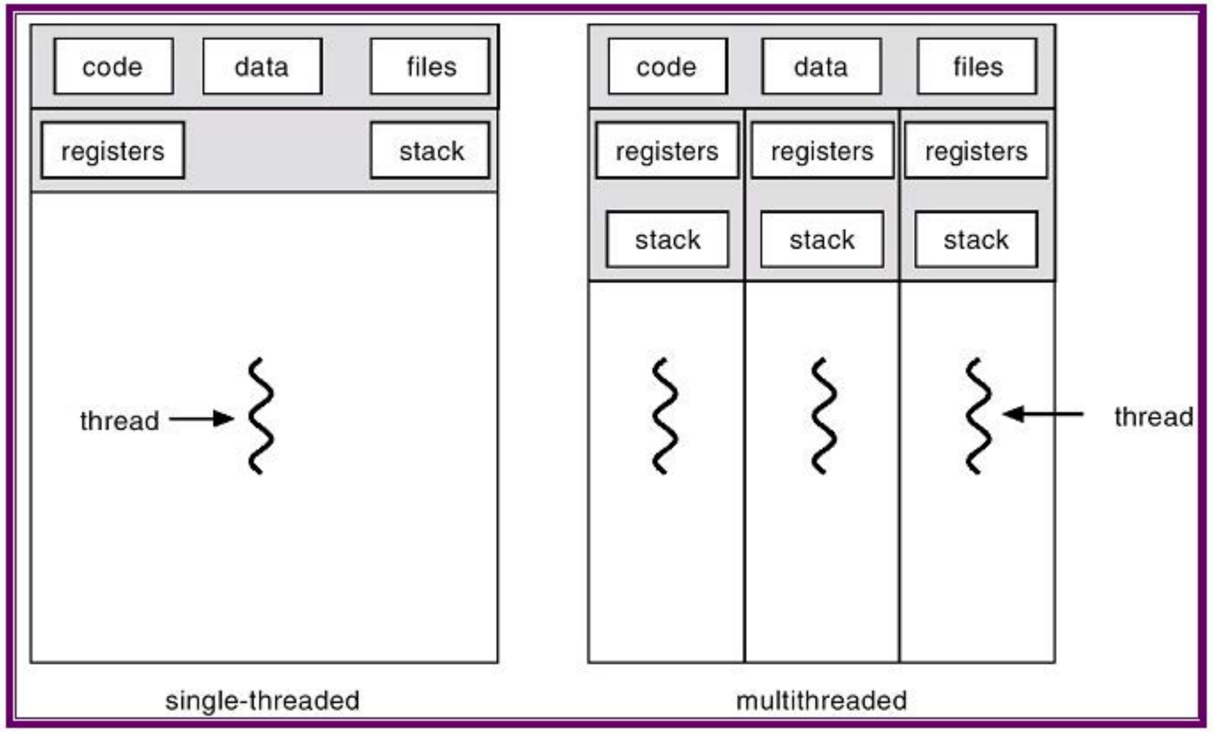




http://www.prace-ri.eu/best-practice-guide-knights-landing-january-2017/#scaling-and-speedup-NPB

## Threads

- Threads are lightweight, possibly parallel processes
- They ***share*** their memory (except stack)
- If done well, threads lead to huge improvements on multi-processor hardware
- If done poorly, threads can cost more than they save
  - ...and cause huge headaches.



http://www.csc.villanova.edu/~mdamian/threads/posixthreads.html

## Structure of a typical threaded program

1. Create a thread that is set to run a defined function at start ("create")
2. Start the treads ("start")
   1. The threads to work
   2. The main thread can do work too
3. Wait for threads to finish ("join")

- The threads often call the same function
  - but do different work based on ID

Psuedo-code for threading structure

```
function runner() {
    id = get_thread_id()
    do_some_work(id)
}

function main() {
    t1 = pthread_create(runner)
    t2 = pthread_create(runner)
    t1.start()
    t2.start()
    /* do something */
    t1.join()
    t2.join()
}
```

## Race conditions

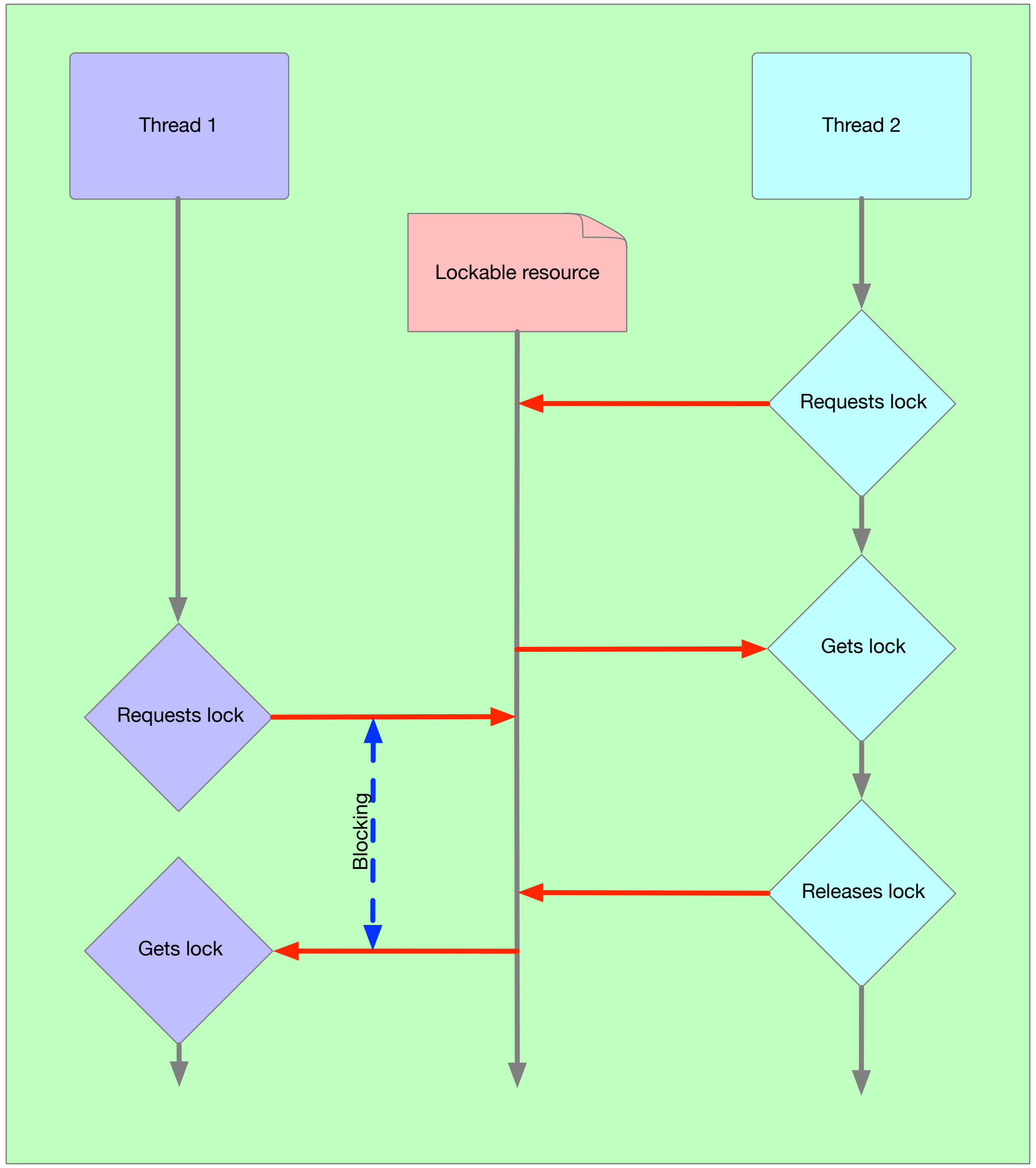
- Suppose t1's job involved writing data to a the file *data*
- While t1 is doing this, t2 is computing some data to add to the file
- After computing t2 reads the file and uses that data to finish its work
- *Usually* t2 takes long enough that *data* is ready
  - *...but what if it's not!*

- **A race condition exists when success of an algorithm depends on one thread/process "winning the race" against another.**

## Locking: Overview

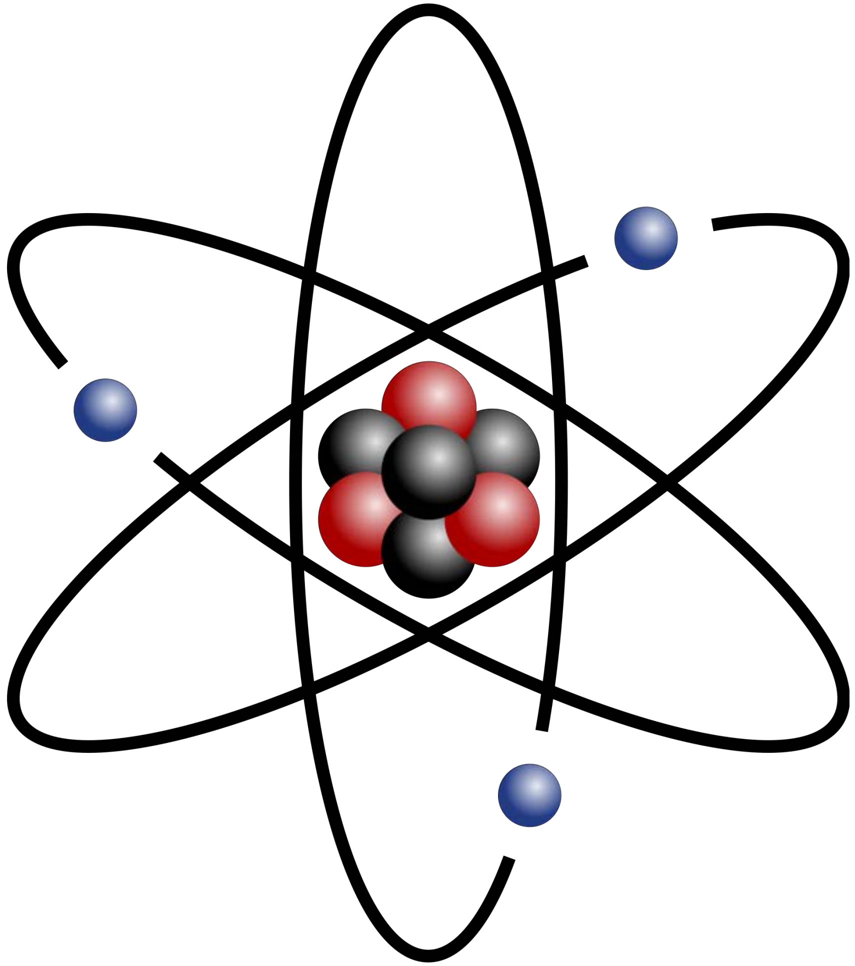
- How do we deal with things like race conditions?
- In our example, if:
  - t1 had a way to maintain exclusive access to *data*
  - ...and t2 would wait until that access was dropped.
    - Then there wouldn't be a race.

- This is an example of Locking.
- Locking can be used to synchronize concurrent computing processes/threads.



## Atomic operations

- An “atomic” operation is guaranteed to complete without interference from any concurrent process.
- Typically, this means they take exactly one instruction cycle on the CPU, making them uninterruptable.
- Atomic operations are the necessary basis for locking & synchronization
  - If we want to lock something, we need to know the the operation of locking isn’t itself a race
    - ...what if two things call lock at the same time?


https://en.wikipedia.org/wiki/Atomic_mass

## Locking: Mutex

- A Mutex has two operations:
  - Lock()
  - Unlock()
- Stores a reference in shared memory
- Uses atomic operations to read/set whether the lock is held
- If you try to Lock() an already locked mutex
  - ...you'll block until it gets Unlock()ed by someone else

https://medium.com/@the1mills/a-better-mutex-for-node-js-4b4897fd9f11

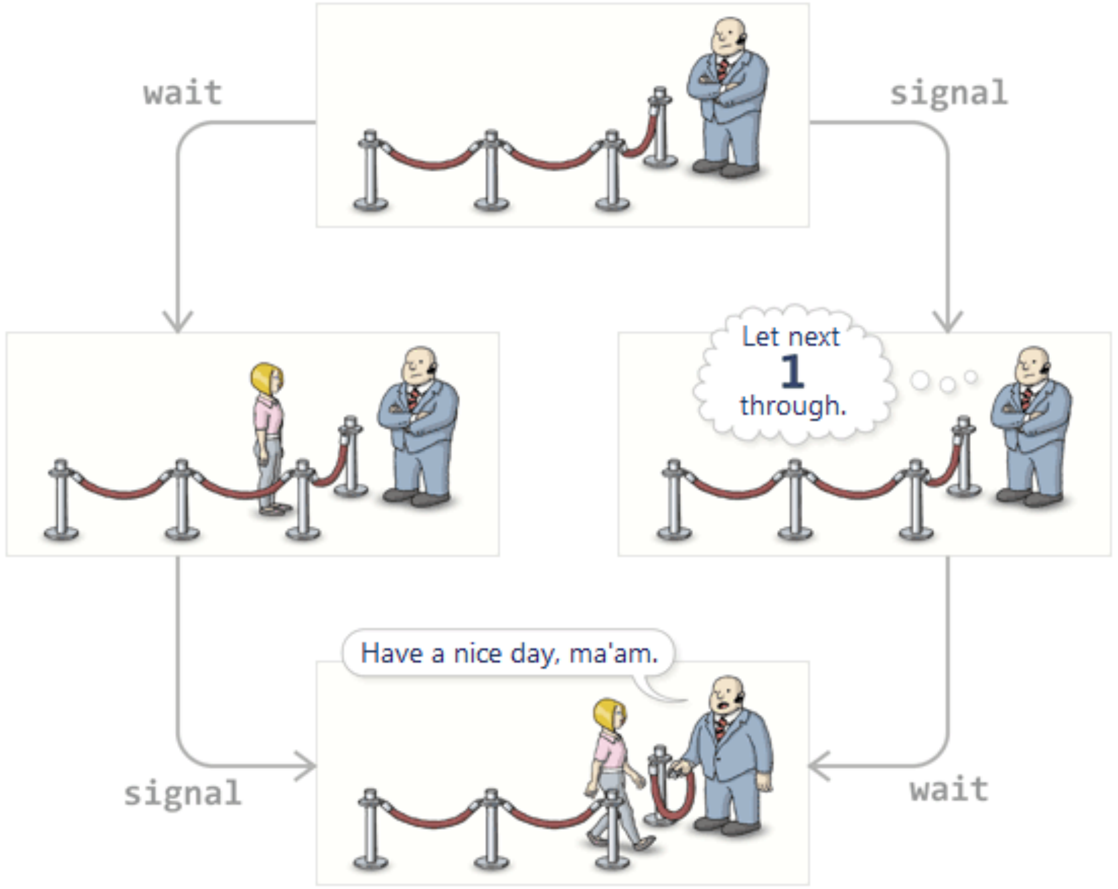
## Locking: RWMutex

- An RWMutex works like Mutex
- But:
  - There can be any number of RLocks() (read)
  - There can be only one WLock() (write)
  - WLock() and RLock() are mutually exclusive
  - Once WLock() is requested, new RLocks() block
    - ...once all RLock()s RUnlock(), WLock() is granted.

## Locking: Semaphore

- Two operations, and an integer:
  - Wait() decrements the integer by 1
    - And waits to be signaled
  - Signal() incriments the integer by 1
    - If the integer goes from < 0 to >= 0, waiting processes are signaled

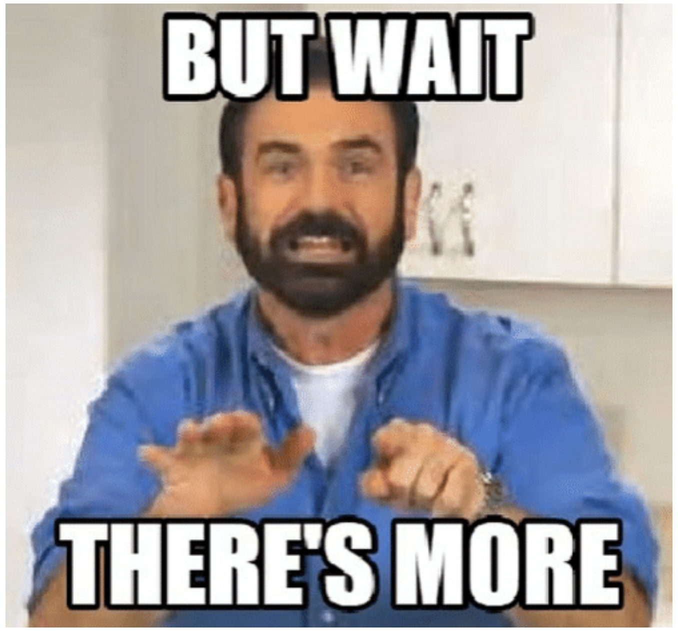
- Like Mutex, based on simple atomic add/subtract atomic operations.
- Can be used to implement things like RWLocks



https://preshing.com/20150316/semaphores-are-surprisingly-versatile/

## Locking: ...but wait! There’s more...

- Barriers: everybody must pause until we all call Barrier (synchronize).
- Conditional locks: lock until a condition is met.
- SpinLock: Like locking, but instead of blocking, pole for the lock.
- Event Locks: Block until this event is raised.



## Deadlocks

- Example:
  1. run1() locks t and calls run2()
  2. run2() tries to lock t, and blocks
     - run2 never exits
     - run1 never continues to t.Unlock()

- This is a *deadlock*.
- A deadlock is a locking condition that has circular dependencies.
- Mostly avoided by careful locking symantics.

Psuedo-code for deadlock

```
function run1() {
    t.Lock()
    run2()
    t.Unlock()
}

function run2() {
    t.Lock()
    do_stuff()
    t.Unlock()
}
```

## Threads aren't the only way

- Multiple processes with inter-process communication
  - Resource expensive, but this is mattering less and less
  - Often use UNIX domain sockets for communication (a special kind of file)
- Thread abstraction layers:
  - OpenMP—C/C++ extensions that give simple parallelism
  - Goroutines—Specific to Golang, message passing between lightweight concurrent routines
  - Event-driven design—register handlers for events, raise events.  Run handlers concurrently.  This is actually how the kernel works.
  - Higher-level abstractions, e.g. Python work queues
- No shared memory at all, but message passing:
  - E.g. MPI (next time)

## OpenMP: Overview

- Standard implemented as “pragmas” (compiler directives)
  - Can be turned on/off for flexible coding & debugging
  - Commonly included within the compiler itself
  - Can vary the number of threads without recoding

- Typically wraps an existing loop, and makes it run in parallel

Psuedo-code for OpenMP structure

```
#include <omp.h>
int main() {
     int cpu_id = -1;
     cpu_id = sched_getcpu( );
...
     #pragma omp parallel for
     for (int i = 0; i < 4; i++){
          printf(“value:%d,
                    thread:%d\n”, i,
                    omp_get_thread_num());
     }
...
}
```

## MPI

## What is MPI?

- “Message Passing Interface”
- A pluggable transport layer for sending bits of data to different processes
- Supports optimized transports for high speed fabrics (e.g. Infiniband)
- Allows efficient, fast inter-process communication across a cluster
- Allows easy porting between clustered platforms

## MPI: History

- 1993 - Draft for standard submitted at supercomputing
- 1994 – MPI 1.0
- 1998 – MPI-2
- 2012 – MPI-3
- MPI-4 – Work in progress...
  - https://www.mpi-forum.org/mpi-40/

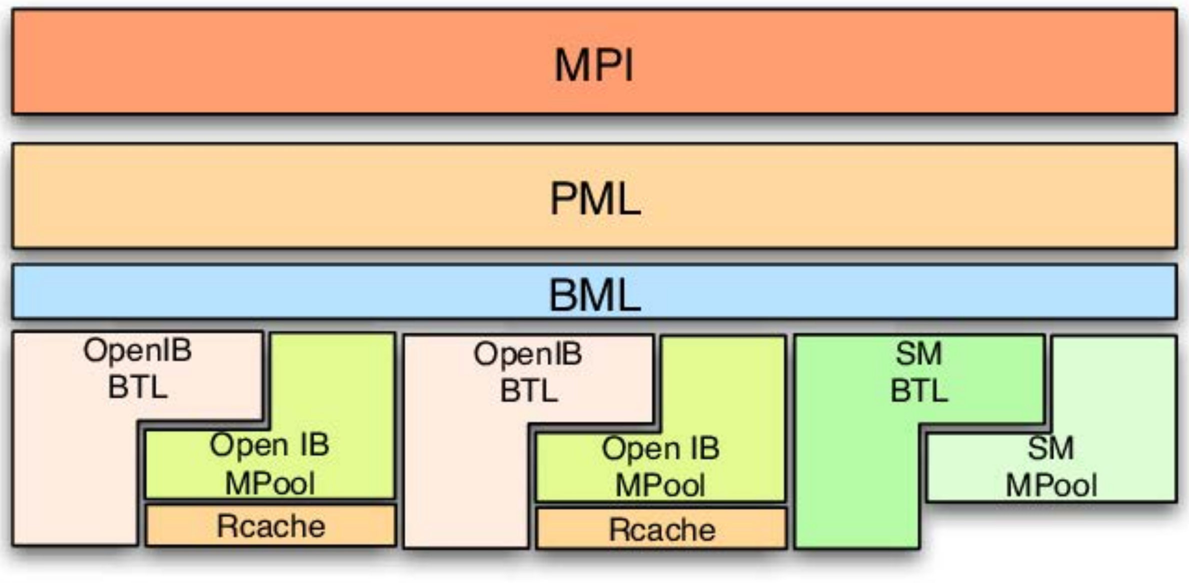
- Some implementations
  - OpenMPI
  - MVAPICH/MPICH
  - Intel MPI
  - IBM BG/Q MPI
  - IBM Spectrum MPI
  - Cray MPI

MVAPICH OPEN MPI intel® IBM CRAY

## OpenMPI stack

- Layered model that abstracts hardware
- Supports various interconnects
- Full support for RDMA
  - ...maps remote memory to local system
- Also supports standard networks like Ethernet

OpenMPI Component Stack



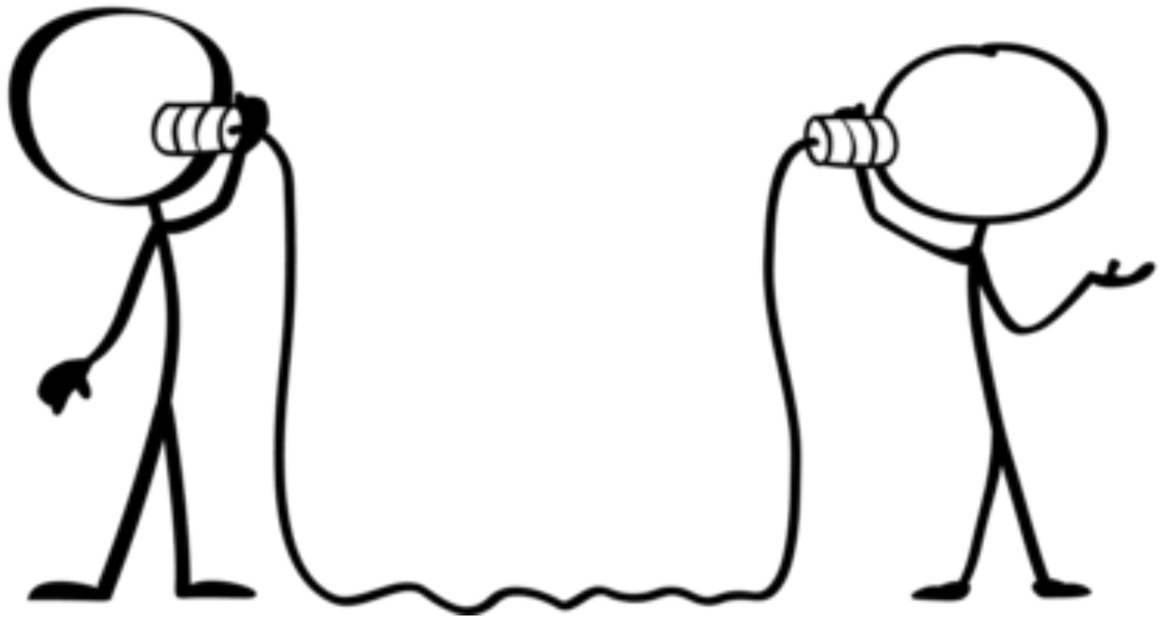
https://open-mpi.org

## Terminology

- **Groups**—multiple processes form a group
- **Context**—a message sent in a context must be received in that context
- **Communicator**—the combination of a group and a context
- **MPI_COMM_WORD**—the default Communicator that talks to all processes
- **Rank**—one instance in an MPI process

## MPI: Point-to-point operations

- **Send/Recv**: send & receive from specific rank to specific rank
  - Several variants:
    - isend/irecv: non-blocking
    - ssend/srecv: syncrhonous mode
- **Sendrecv**: send/recv, but both ends use the same function call
- Common use case:
  - Send information to immediate neighbors in grid



https://www.weshigbee.com/direct-communication-isnt-what-it-seems/

## MPI: Collective operations

- Collective operations are some of the most useful parts of MPI
- Allow for coordination of a large number of ranks trivially
- Common uses:
  - Collect divide-and-conquer pieces of data into central location
  - Distribute work to workers
  - Update global state information

- **Scatter** – split a list and send a piece to each rank
- **Gather** – collect data from all ranks to one rank
- **Allgather** – collect data from all ranks to all ranks
- **Bcast** – send data from one rank to all ranks
- **Reduce** – reduce many values to one with a basic operation
- **Allreduce** – reduce many values to one with a basic operation, send to all ranks
- ...

## Questions?