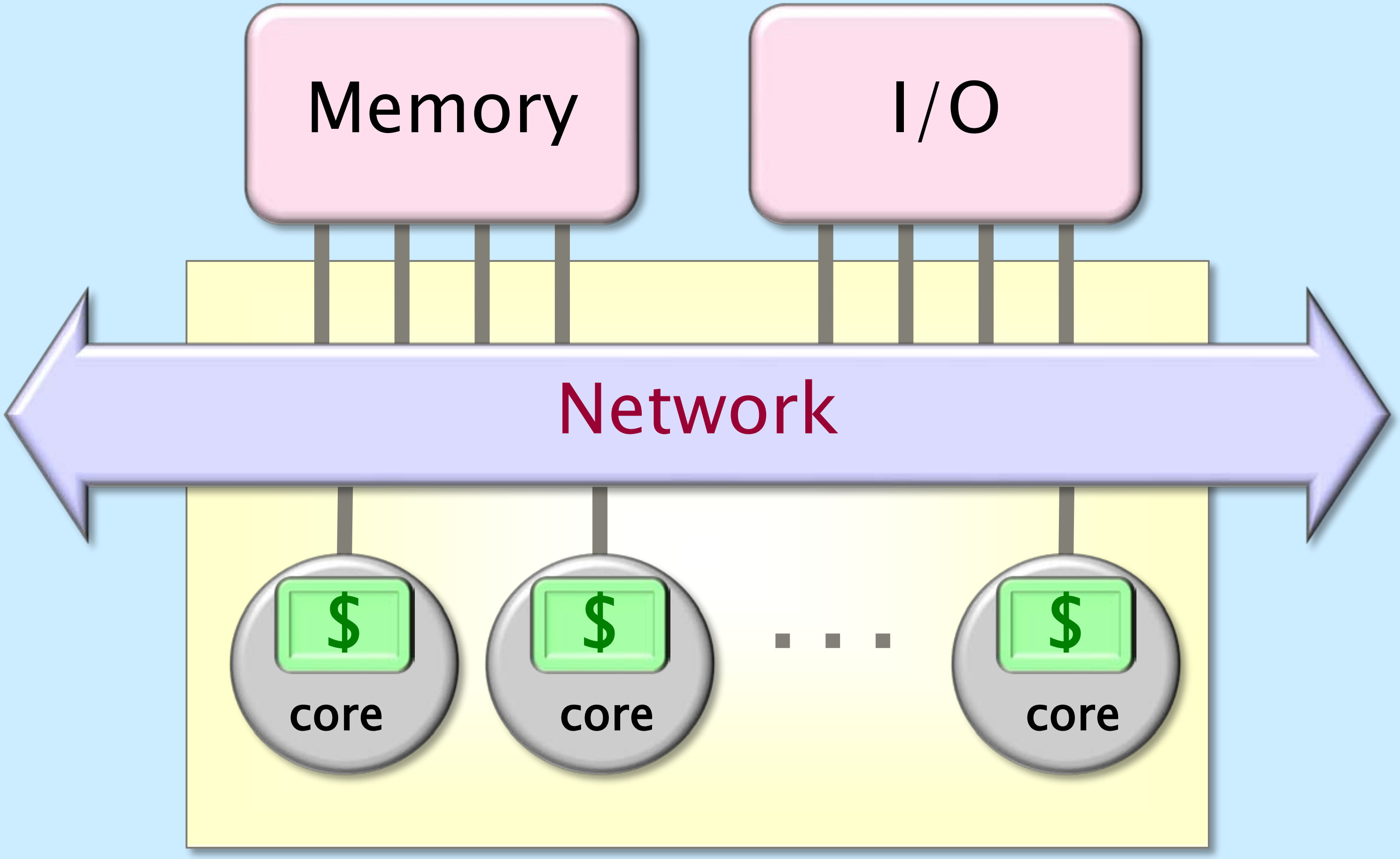
# CS 140 : Jan 31 – Feb 7, 2011 Multicore (and Shared Memory) Programming with Cilk++

- Multicore and NUMA architectures
- Multithreaded Programming
- Cilk++ as a concurrency platform
- Divide and conquer paradigm for Cilk++

Thanks to Charles E. Leiserson for some of these slides

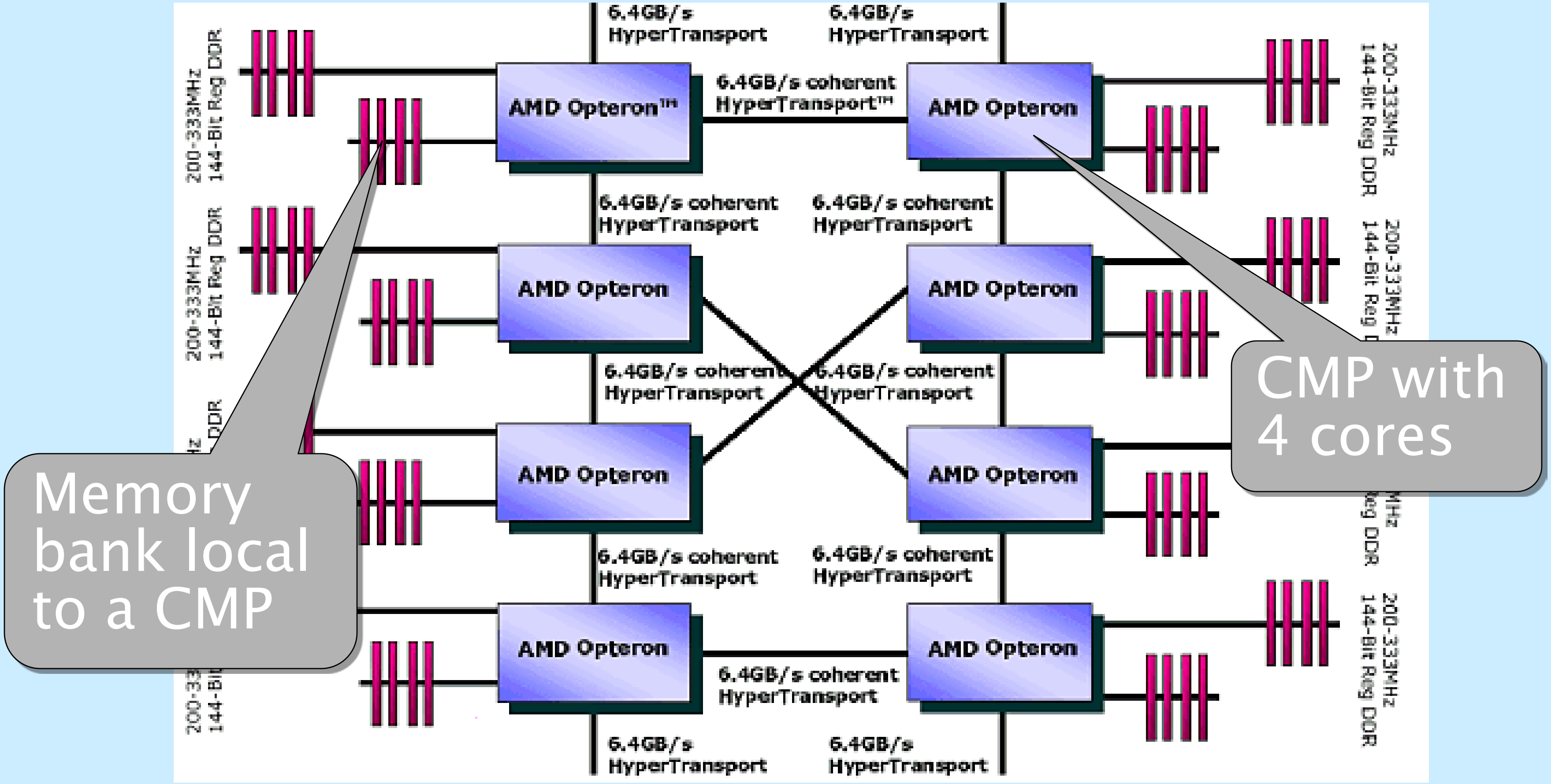
# Multicore Architecture




Chip Multiprocessor (CMP)

# cc-NUMA Architectures

## AMD 8-way Opteron Server (neumann@cs.ucsb.edu)

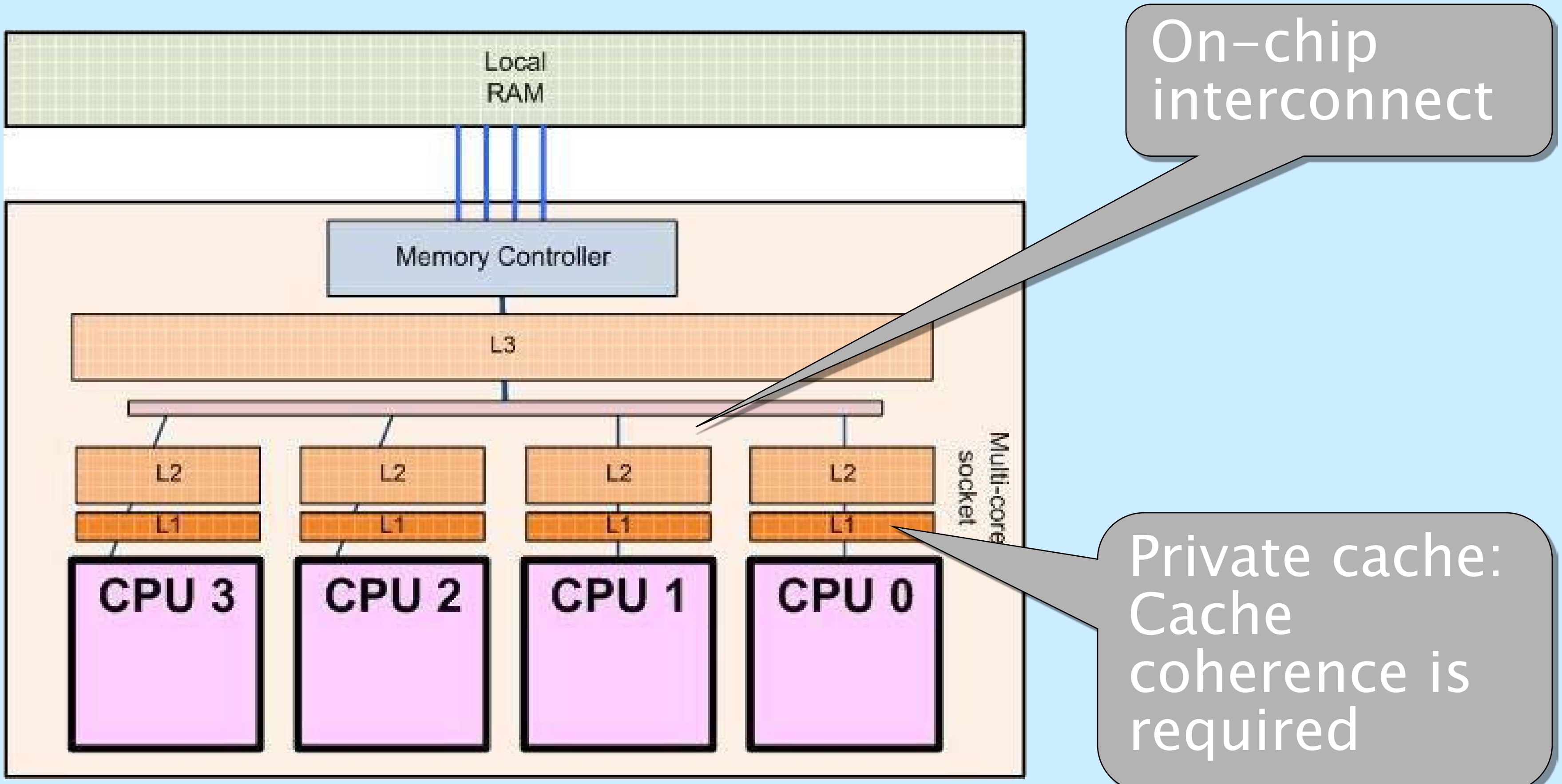


# cc-NUMA Architectures

- No Front Side Bus
- Integrated memory controller
- On-die interconnect among CMPs
- Main memory is physically distributed among CMPs -- each piece of memory has an affinity to one CMP
- NUMA: Non-uniform memory access
  - For multi-socket servers only
  - Your laptop is safe (well, for now at least)
  - Triton nodes are also NUMA !

# Desktop Multicores Today

**This is your AMD Shangai or Intel Core i7 (Nehalem) !**



# Multithreaded Programming

- A **thread of execution** is a fork of a computer program into two or more concurrently running tasks.
- POSIX Threads (Pthreads) is a set of threading interfaces developed by the IEEE
- Assembly of shared memory programming
- Programmer has to manually:
  - Create and terminating threads
  - Wait for threads to complete
  - Manage the interaction between threads using mutexes, condition variables, etc.

# Concurrency Platforms

- Programming directly on PThreads is painful and error-prone.
- With PThreads, you either sacrifice memory usage or load-balance among processors
- A ***concurrency platform*** provides linguistic support and handles load balancing.
- Examples:
  - Threading Building Blocks (TBB)
  - OpenMP
  - Cilk++

# Cilk vs. PThreads

How will the following code execute in PThreads? In Cilk?

```
for (i=1; i<1000000000; i++) {
   spawn-or-fork foo(i);
}
sync-or-join;
```

What if foo contains code that waits (e.g., spins) on a variable being set by another instance of foo?

This difference is a liveness property:

- Cilk threads are spawned lazily, “may” parallelism
- PThreads are spawned eagerly, “must” parallelism

# Cilk vs. OpenMP

- Cilk++ guarantees space bounds.
  On P processors, Cilk++ uses no more than P times the stack space of a serial execution.
- Cilk++ has serial semantics.
- Cilk++ has a solution for global variables (a construct called "hyperobjects")
- Cilk++ has nested parallelism that works and provides guaranteed speed-up.
- Cilk++ has a race detector for debugging and software release.

# Great, how do we program in it?

- Cilk++ is a faithful extension of C++
- Programmers implement algorithms mostly in the **divide-and-conquer** paradigm. Two hints to the compiler:
  - cilk_spawn: *the following function can run in parallel with the caller.*
  - cilk_sync: *all spawned children must return before program execution can continue*
- Third keyword for programmer convenience only (compiler converts it to spawns & syncs under the covers)
  - cilk_for

# Nested Parallelism

## Example: Quicksort

```
template <typename T>
void qsort(T begin, T end) {
  if (begin != end) {
     T middle = partition(
                  begin,
                  end,
                  bind2nd( less<typename iterator_traits<T>::value_type>(),
                           *begin )
               );
     cilk_spawn qsort(begin, middle);
     qsort(max(begin + 1, middle), end);
     cilk_sync;
  }
}
```

The named ***child*** function may execute in parallel with the ***parent*** caller.

Control cannot pass this point until all spawned children have returned.

# Cilk++ Loops

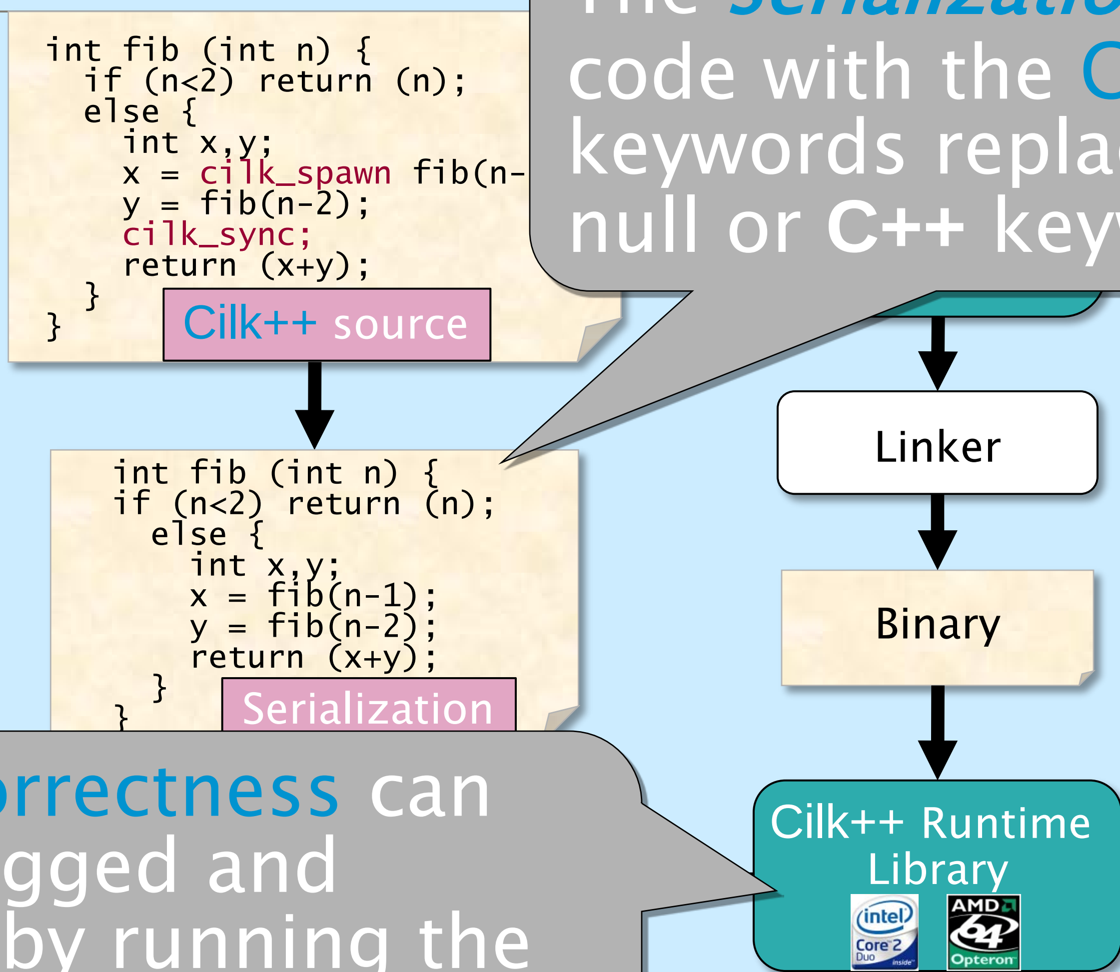
## Example: Matrix transpose

```
cilk_for (int i=1; i<n; ++i) {
    cilk_for (int j=0; j<i; ++j) {
        B[i][j] = A[j][i];
    }
}
```

- A `cilk_for` loop's iterations execute in parallel.
- The index must be declared in the loop initializer.
- The end condition is evaluated exactly once at the beginning of the loop.
- Loop increments should be a **const** value

# Serial Correctness

The *serialization* is the code with the Cilk++ keywords replaced by null or **C++** keywords.




Serial correctness can be debugged and verified by running the multithreaded code on a single processor.

# Serialization

How to seamlessly switch between serial c++ and parallel cilk++ programs?

```
#ifdef CILKPAR
   #include <cilk.h>
#else
   #define cilk_for for
   #define cilk_main main
   #define cilk_spawn
   #define cilk_sync
#endif
```

Add to the beginning of your program

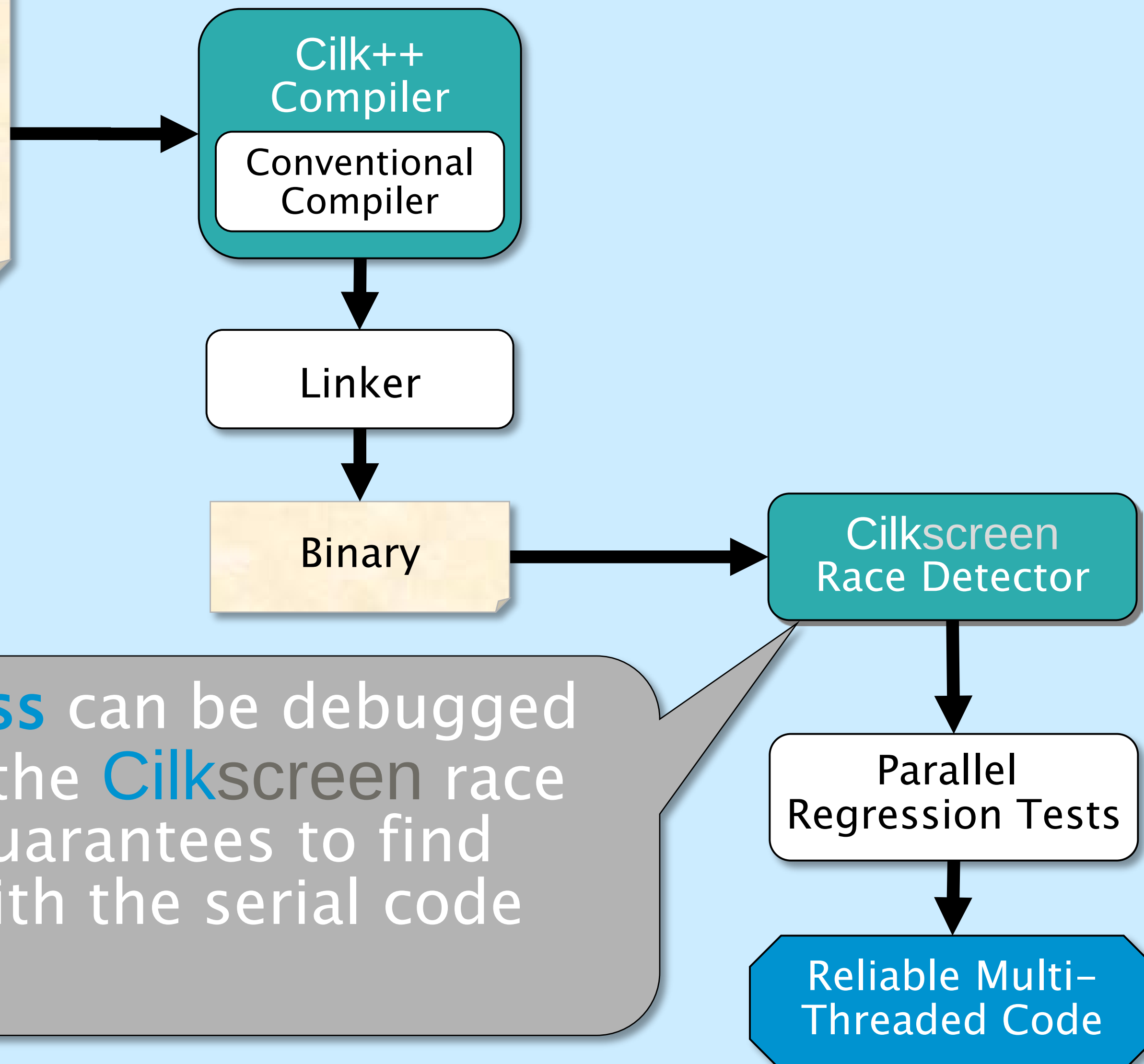
Compile !

- cilk++ -DCILKPAR -O2 -o parallel.exe main.cpp
- g++ -O2 -o serial.exe main.cpp

# Parallel Correctness

```
int fib (int n) {
  if (n<2) return (n);
  else {
    int x,y;
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
    cilk_sync;
    return (x+y);
  }
}
```

Cilk++ source



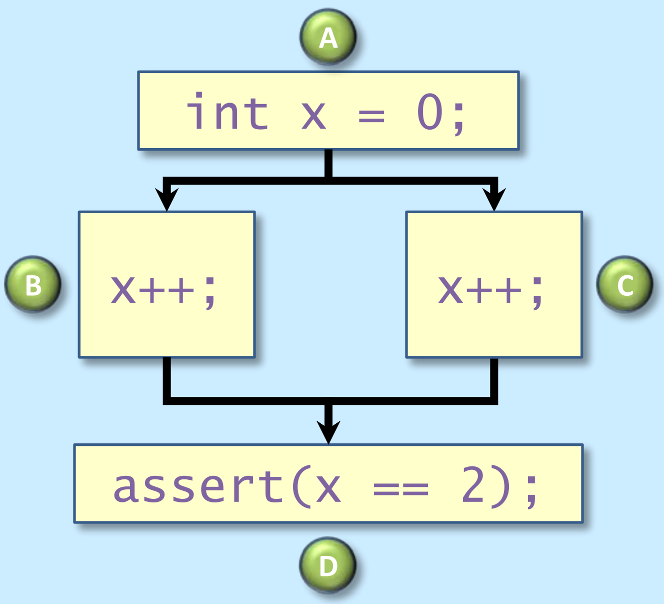

Parallel correctness can be debugged and verified with the Cilkscreen race detector, which guarantees to find inconsistencies with the serial code quickly.

# Race Bugs

**Definition.** A *determinacy race* occurs when two logically parallel instructions access the same memory location and at least one of the instructions performs a write.

## Example

```
int x = 0;
cilk_for(int i=0, i<2, ++i) {
    x++;
}
assert(x == 2);
```




*Dependency Graph*

# Race Bugs

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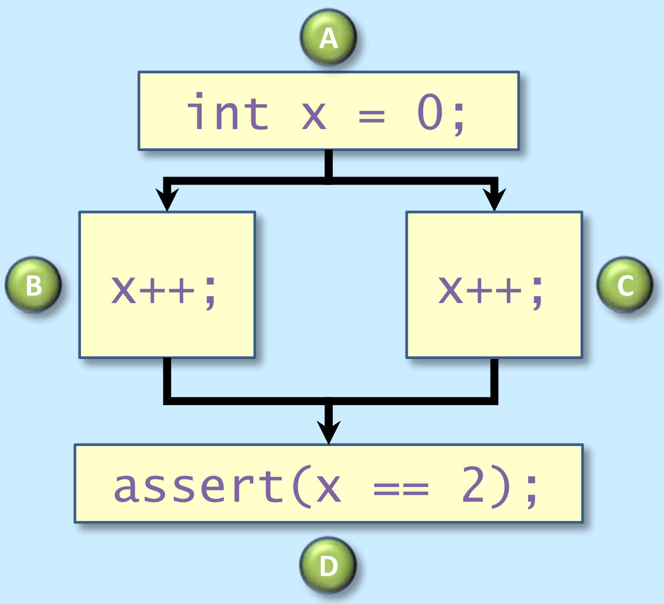
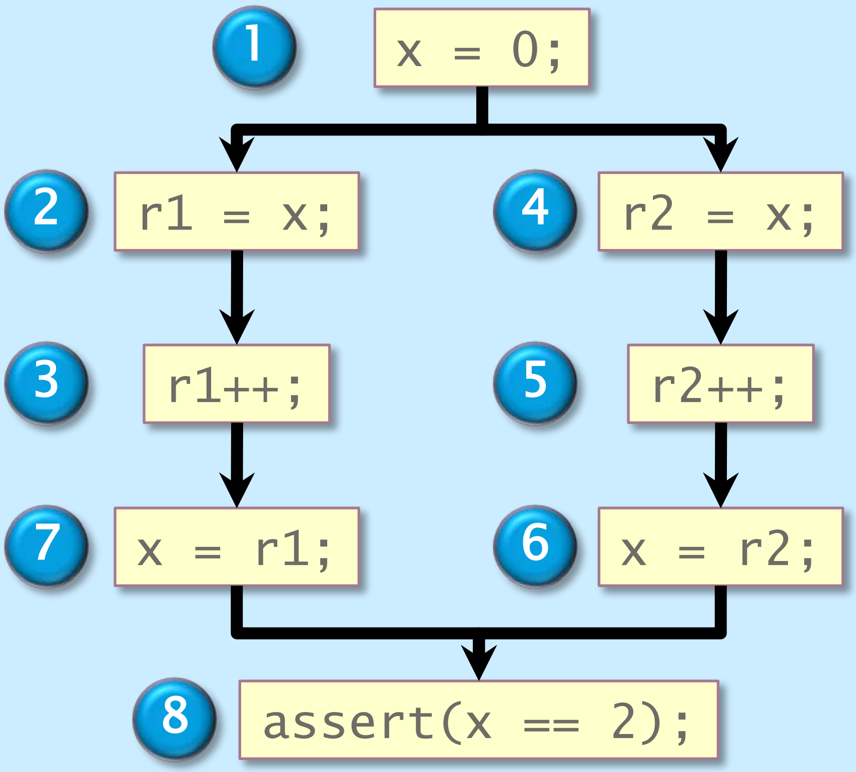


# Types of Races

Suppose that instruction A and instruction B both access a location x, and suppose that $A \parallel B$ (A is parallel to B).

| A | B | Race Type |
|---|---|---|
| read | read | none |
| read | write | read race |
| write | read | read race |
| write | write | write race |

Two sections of code are *independent* if they have no determinacy races between them.

# Avoiding Races

- All the iterations of a `cilk_for` should be independent.
- Between a `cilk_spawn` and the corresponding `cilk_sync`, the code of the spawned child should be independent of the code of the parent, including code executed by additional spawned or called children.

Ex.

```
cilk_spawn qsort(begin, middle);
qsort(max(begin + 1, middle), end);
cilk_sync;
```

*Note:* The arguments to a spawned function are evaluated in the parent before the spawn occurs.

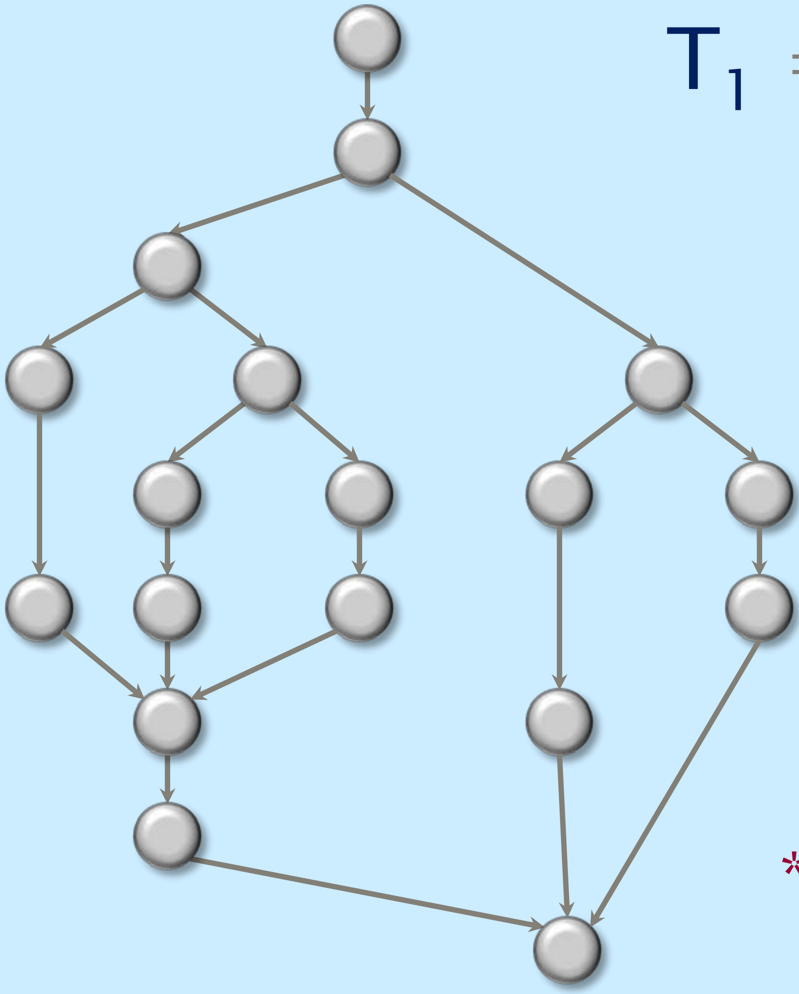
# Cilkscreen

- Cilkscreen runs off the binary executable:
  - Compile your program with the `-fcilkscreen` option to include debugging information.
  - Go to the directory with your executable and execute `cilkscreen` *`your_program`* `[`*`options`*`]`
  - Cilkscreen prints information about any races it detects.
- For a given input, Cilkscreen mathematically guarantees to localize a race if there exists a parallel execution that could produce results different from the serial execution.
- It runs about 20 times slower than real-time.

# Complexity Measures

$T_P$ = execution time on $P$ processors

$T_1$ = *work* $T_\infty$ = *span**



**WORK LAW**

- $T_P \geq T_1/P$

**SPAN LAW**

- $T_P \geq T_\infty$

*Also called *critical-path length* or *computational depth*.

# Speedup

***Def.*** $T_1/T_P =$ ***speedup*** on $P$ processors.

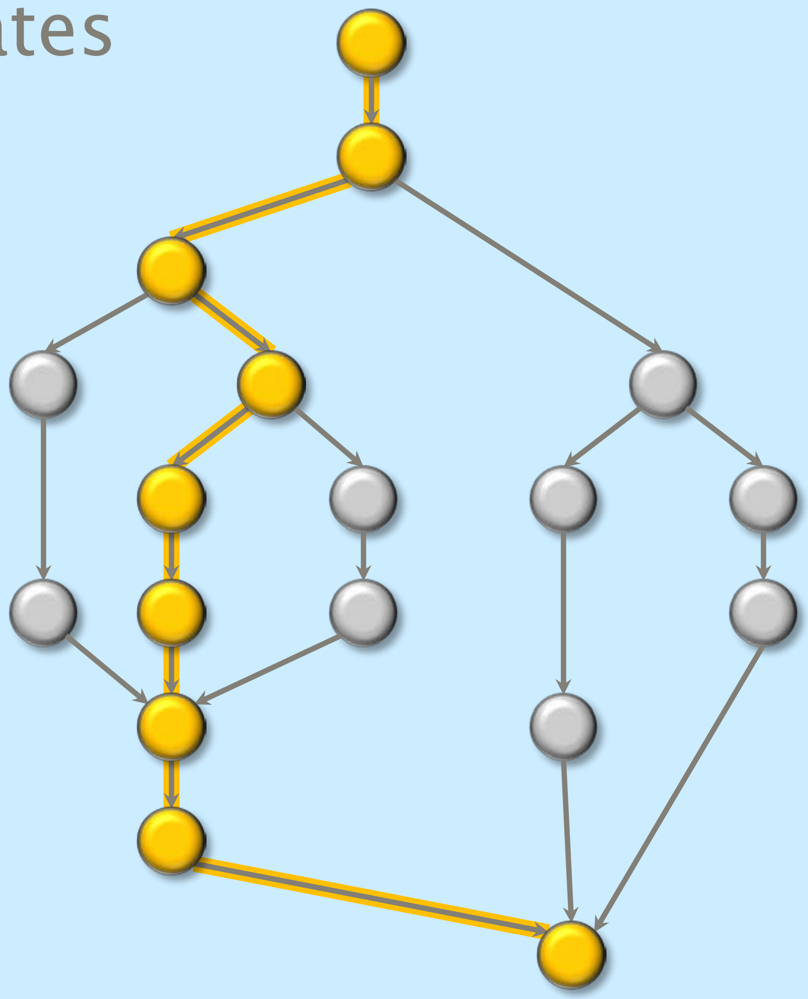
If $T_1/T_P = \Theta(P)$, we have ***linear speedup***,
$= P$, we have ***perfect linear speedup***,
$> P$, we have ***superlinear speedup***,
which is not possible in this performance model, because of the Work Law $T_P \geq T_1/P$.

# (Potential) Parallelism

Because the Span Law dictates that $T_P \geq T_\infty$, the maximum possible speedup given $T_1$ and $T_\infty$ is

$T_1/T_\infty$ = ***parallelism***

= the average amount of work per step along the span.



# Three Tips on Parallelism

1. *Minimize the span* to maximize parallelism. Try to generate 10 times more parallelism than processors for near-perfect linear speedup.
2. If you have plenty of parallelism, try to trade some if it off for *reduced work overheads*.
3. Use *divide-and-conquer recursion* or *parallel loops* rather than spawning one small thing off after another.

*Do this:*

```
cilk_for (int i=0; i<n; ++i) {
    foo(i);
}
```

*Not this:*

```
for (int i=0; i<n; ++i) {
    cilk_spawn foo(i);
}
cilk_sync;
```

# Three Tips on Overheads

1. Make sure that work/#spawns is not too small.
   - Coarsen by using function calls and *inlining* near the leaves of recursion rather than spawning.
2. Parallelize *outer loops* if you can, not inner loops. If you must parallelize an inner loop, coarsen it, but not too much.
   - 500 iterations should be plenty coarse for even the most meager loop.
   - Fewer iterations should suffice for "fatter" loops.
3. Use *reducers* only in sufficiently fat loops.

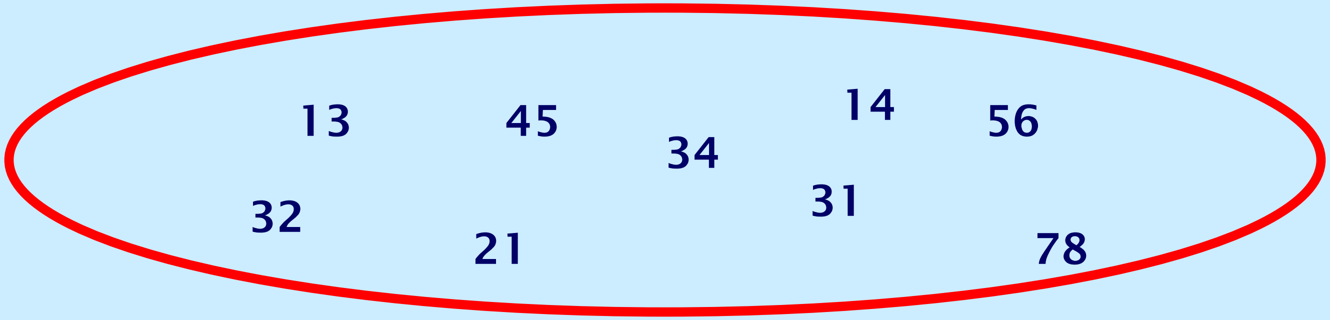
# Sorting

- Sorting is possibly the most frequently executed operation in computing!
- **Quicksort** is the fastest sorting algorithm in practice with an average running time of O(N log N), (but $O(N^2)$ worst case performance)
- **Mergesort** has worst case performance of O(N log N) for sorting N elements
- Both based on the recursive **divide-and-conquer** paradigm

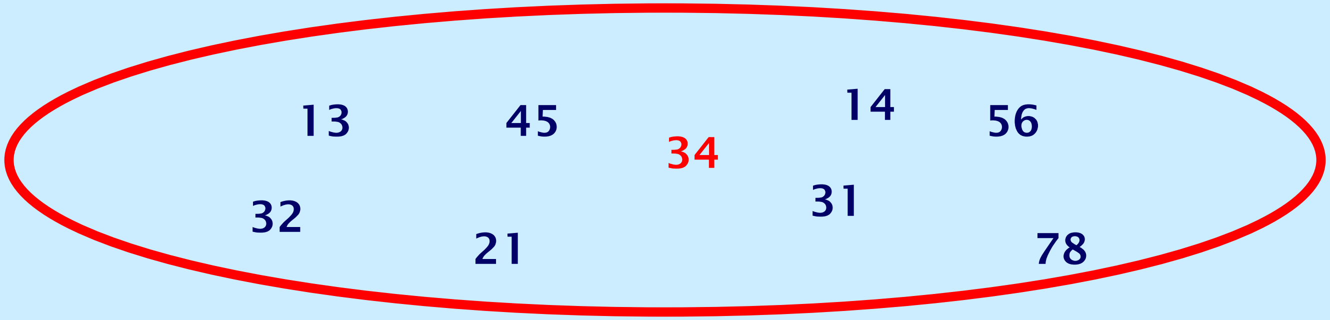
# QUICKSORT

- Basic Quicksort sorting an array S works as follows:
  - If the number of elements in S is 0 or 1, then return.
  - Pick any element *v* in S. Call this pivot.
  - Partition the set S–{v} into two disjoint groups:
    - $S_1 = \{x \varepsilon S-\{v\} \mid x \leq v\}$
    - $S_2 = \{x \varepsilon S-\{v\} \mid x \geq v\}$
  - **Return quicksort($S_1$) followed by v followed by quicksort($S_2$)**

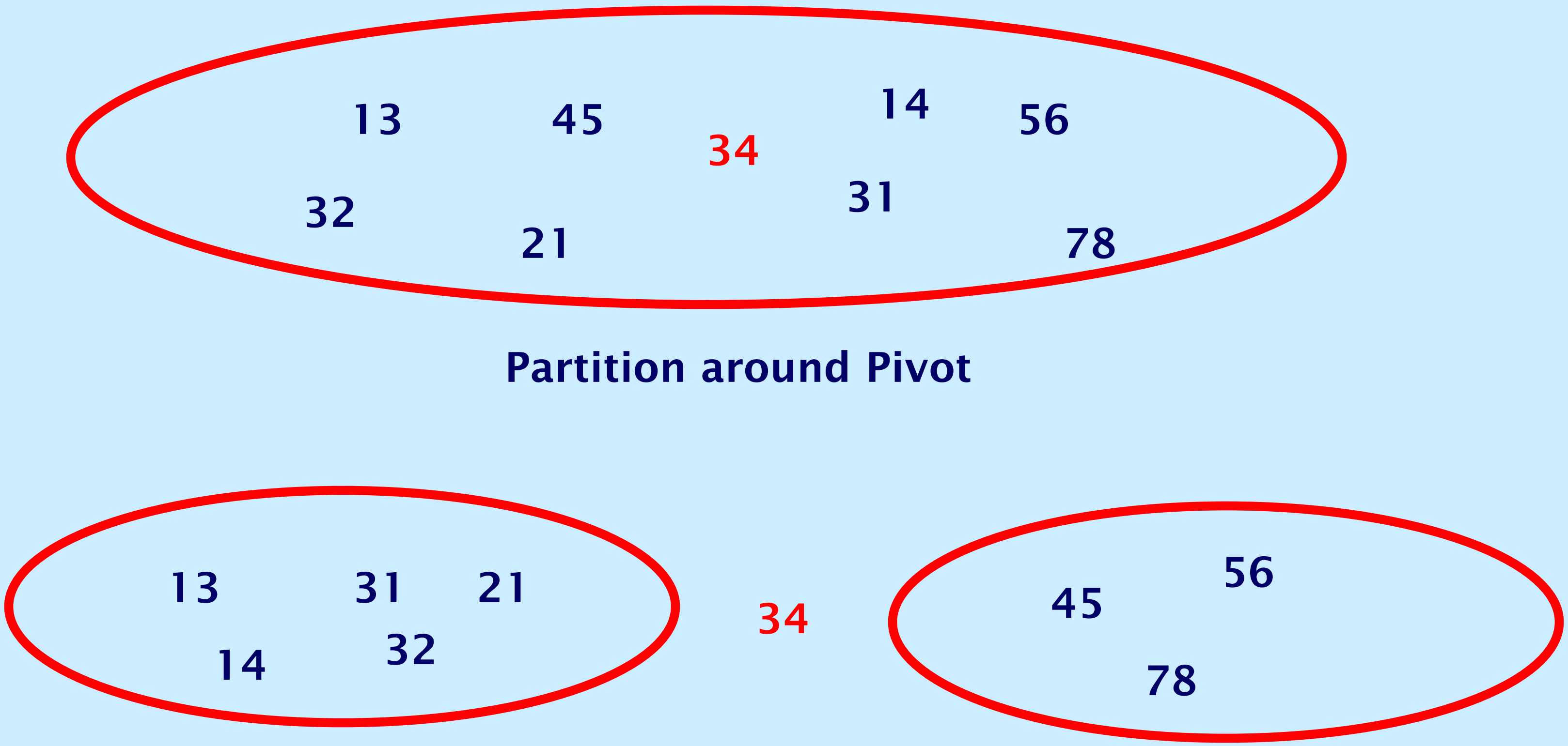
# QUICKSORT




Select Pivot

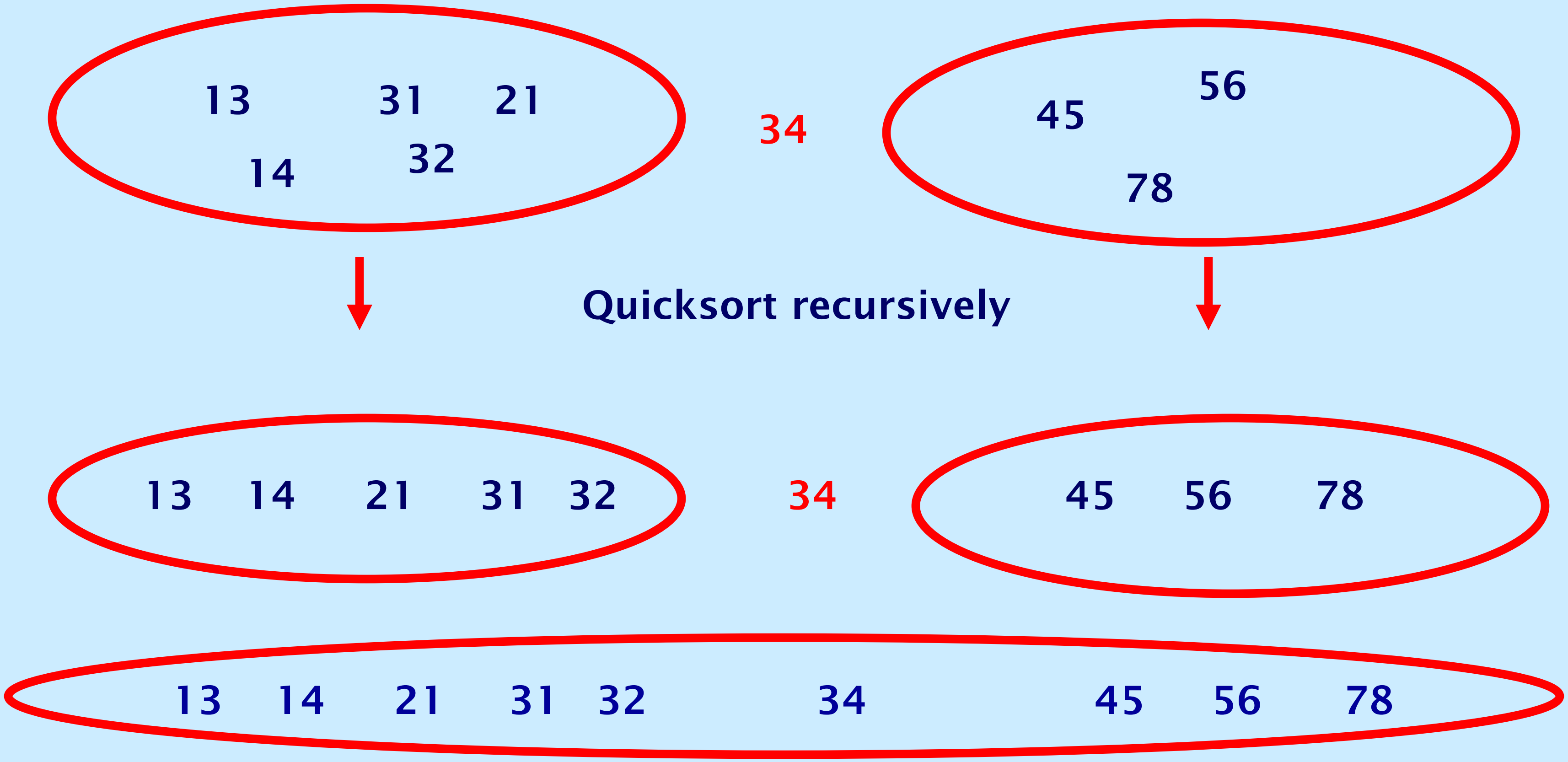


# QUICKSORT



13
45
34
14
56
32
21
31
78
Partition around Pivot
13
31
21
14
32
34
56
45
78

# QUICKSORT


13 31 21
14 32
34
56
45
78
Quicksort recursively
13 14 21 31 32
34
45 56 78
13 14 21 31 32 34 45 56 78