More Shared-memory Parallel Programming with Cilk Plus

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Last Thursday

- Threaded programming models
- Introduction to Cilk Plus
  - tasks
  - algorithmic complexity measures
  - scheduling
  - performance and granularity
  - task parallelism examples
    - vector addition using divide and conquer
    - nqueens: exploratory search

Outline for Today

- **Cilk Plus**
  - explore speedup and granularity
  - task parallelism example
    - cilksort
  - parallel loops
  - reducers
- **Data race detection with cilkscreen**
- **Assessing Cilk Plus performance with cilkview**

Review: Cilk Plus Parallel Performance Model

$$c_1 = \frac{T_1}{T_s}$$

work overhead

$$T_p \le c_1 \frac{T_s}{P} + c_\infty T_\infty$$

"Minimize work overhead (c_1) at the expense of a larger critical path overhead (c_∞), because work overhead has a more direct impact on performance"

$$T_p \approx c_1 \frac{T_s}{P}$$

assuming parallel slackness

Speedup Demo

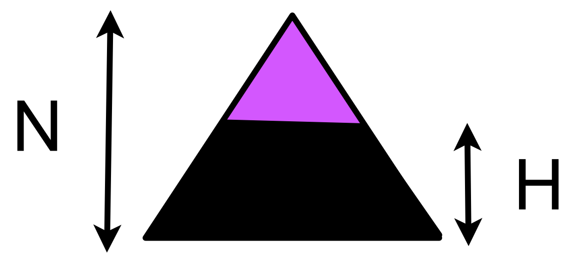
Explore speedup of naive fibonacci program

- `cp /projects/comp422/cilkplus-examples/fib ~/fib`
- `cd ~/fib`
- fib.cpp: a program for computing n^{th} fibonacci #
- experiment with the fibonacci program
  - `make runp W=n` *computes fib(44) with n workers*
  - compute fib(44) for different values of W, 1 ≤ W ≤ 12
  - what value of W yields the lowest execution time?
  - what is the speedup vs. the execution time of "`./fib-serial 44`"?
  - how does this speedup compare to the total number of HW threads?

Granularity Demo

Explore how changing increasing the granularity of parallel work in fib improves performance (by reducing c_1)

- fib-trunc.cpp: a program for computing n^{th} fibonacci #
  - this version differs in that one can execute subtrees of height H sequentially rather than spawning parallel tasks all the way down
- build the examples: `make`
- experiment with the fibonacci program with truncated parallelism
  - `make runt H=h` *computes fib(44) with lowest H levels serial*
  - compute fib(44) for different values of H, 2 ≤ H ≤ 44
  - what value of H yields the lowest execution time?
  - what is the speedup vs. the execution time of "`./fib-serial 44`"?
  - how does this speedup compare to the total number of HW threads?



Cilk Performance Model in Action

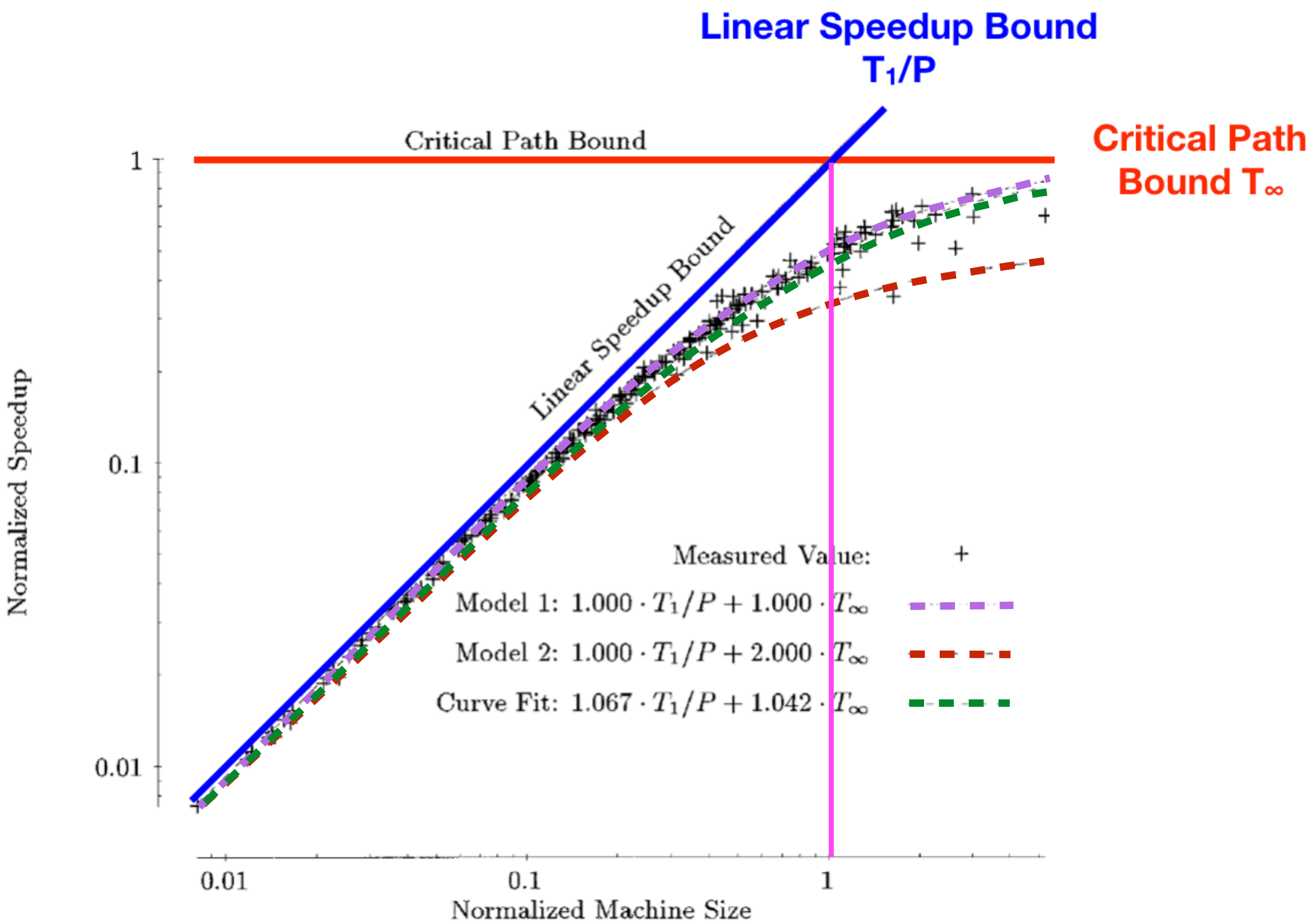


FIG. 8. Normalized speedups for the ★Socrates chess program.

The normalized machine size is 1 when $T_1/T_\infty = P$

Cilksort

Variant of merge sort

```
void cilksort(ELM *low, ELM *tmp, long size) {
    long quarter = size / 4;
    ELM *A, *B, *C, *D, *tmpA, *tmpB, *tmpC, *tmpD;
    if (size < QUICKSIZE) { seqquick(low, low + size - 1) return; }

    A = low; tmpA = tmp;
    B = A + quarter; tmpB = tmpA + quarter;
    C = B + quarter; tmpC = tmpB + quarter;
    D = C + quarter; tmpD = tmpC + quarter;

    cilk_spawn cilksort(A, tmpA, quarter);
    cilk_spawn cilksort(B, tmpB, quarter);
    cilk_spawn cilksort(C, tmpC, quarter);
    cilksort(D, tmpD, size - 3 * quarter);
    cilk_sync;

    cilk_spawn cilkmerge(A, A + quarter - 1, B, B + quarter - 1, tmpA);
    cilkmerge(C, C + quarter - 1, D, low + size - 1, tmpC);
    cilk_sync;

    cilkmerge(tmpA, tmpC - 1, tmpC, tmpA + size - 1, A);
}
```

Merging in Parallel

- How can you incorporate parallelism into a merge operation?
- Assume we are merging two sorted sequences A and B
- Without loss of generality, assume A larger than B

Algorithm Sketch

1. Find median of the elements in A and B (considered together).
2. Do binary search in A and B to find its position. Split A and B at this place to form A_1, A_2, B_1, and B_2
3. In parallel, recursively merge A_1 with B_1 and A_2 with B_2

Optimizing Performance of cilksort

- Recursively subdividing all the way to singletons is <u>expensive</u>
- When size(remaining sequence) to sort or merge is small (2K)
  - use sequential quicksort
  - use sequential merge

'

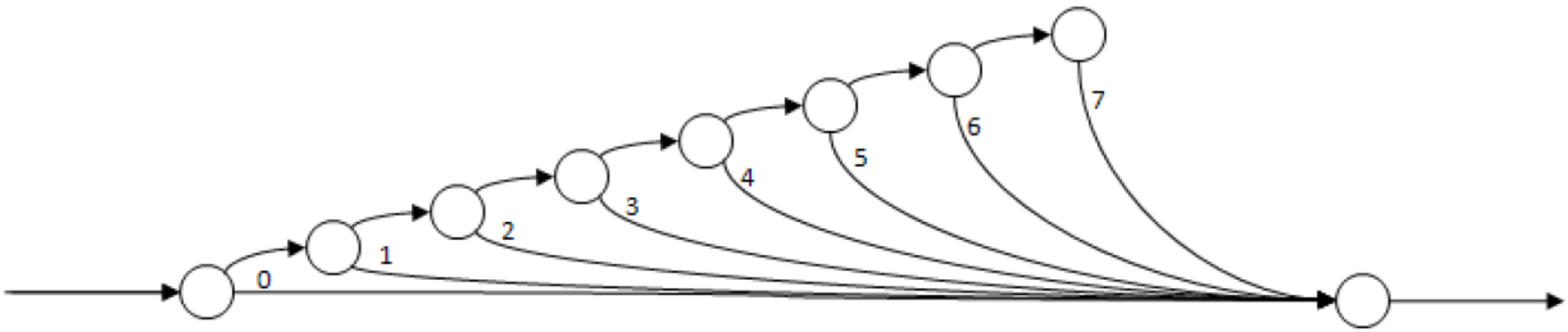
Cilk Plus Parallel Loop: cilk_for

```
cilk_for (T v = begin; v < end; v++) {
      statement_1;
      statement_2;
      ...
}
```

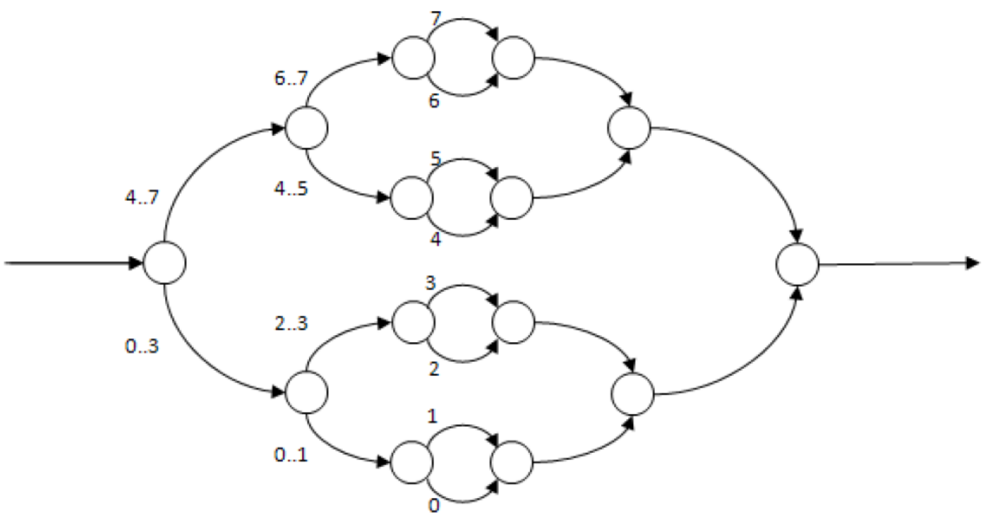
- Loop index v
  - type T can be an integer, ptr, or a *C++ random access iterator*
- Main restrictions
  - runtime must be able to compute total # of iterations on entry to cilk_for
    - must compare v with end value using <, <=, !=, >=, or >
    - loop increment must use ++, --, +=, v = v + incr, or v = v - incr
      - if v is not a signed integer, loop must count up
- Implicit cilk_sync at the end of a cilk_for

Loop with a cilk_spawn vs. cilk_for

- for (int i = 0; i < 8; i++) { cilk_spawn work(i); } cilk_sync;



- cilk_for (int i = 0; i < 8; i++) { work(i);}



Note: computation on edges

cilk_for uses divide-and-conquer

Figure credits: Intel Cilk++ Programmer's Guide. Document # 322581-001US.

Restrictions for cilk_for

- No early exit
  - —no break or return statement within loop
  - —no goto in loop unless target is within loop body
- Loop induction variable restrictions
  - —cilk_for (unsigned int i, j = 42; j < 1; i++, j++) { ... }
    - – only one loop variable allowed
  - —cilk_for (unsigned int i = 1; i < 16; ++i) i = f();
    - – can't modify loop variable within loop
  - —cilk_for (unsigned int i = 1; i < x; ++i) x = f();
    - – can't modify end within loop
  - —int i; cilk_for (i = 0; i<100; i++) { ... }
    - – loop variable must be declared in loop header

cilk_for Implementation Sketch

- **Recursive bisection used to subdivide iteration space down to chunk size**

```
void run_loop(first, last)
{

    if (last - first) < grainsize)
    {
        for (int i=first; i<last ++i) LOOP_BODY;
    }
    else
    {
        int mid = (last-first)/2;
        cilk_spawn run_loop(first, mid);
        run_loop(mid, last);
    }
}
```

cilk_for Grain Size

- Iterations divided into *chunks* to be executed serially
  — chunk is sequential collection of one or more iterations
- Maximum size of chunk is called *grain size*
  — grain size too small: spawn overhead reduces performance
  — grain size too large: reduces parallelism and load balance
- Default grain size
  — #pragma cilk grainsize = min(2048, N / (8*p))
- Can override default grain size
  — #pragma cilk grainsize = expr
    – expr is any C++ expression that yields an integral type (e.g. int, long)

      e.g. #pragma cilk grainsize = n/(4*__cilkrts_get_nworkers())

  — pragma must immediately precede cilk_for to which it applies

Parallelizing Vector Addition

C

```
void vadd (real *A, real *B, int n){
  int i; for (i=0; i<n; i++) A[i]+=B[i];
}
```

Cilk Plus

```
void vadd (real *A, real *B, int n){
  if (n<=BASE) {
    int i; for (i=0; i<n; i++) A[i]+=B[i];
  } else {
    cilk_spawn vadd (A, B, n/2);
    vadd (A+n/2, B+n/2, n-n/2);
  }
}
```

```
void vadd (real *A, real *B, int n){
  int i; cilk_for (i=0; i<n; i++) A[i]+=B[i];
}
```

The Problem with Non-local Variables

- **Nonlocal variables are a common programming construct**
  - — global variables = nonlocal variables in outermost scope
  - — nonlocal = declared in a scope outside that where it is used
- **Example**

```
int sum = 0;
for(int i=1; i<n; i++) {
  sum += i;
}
```

- **Rewriting parallel applications to avoid them is painful**

Understanding a Data Race

- **Example**

```
int sum = 0;
cilk_for(int i=1; i<n; i++) {
  sum += i;
}
```

- **What can go wrong?**
  - **concurrent reads and writes can interleave in unpredictable ways**

time ↓

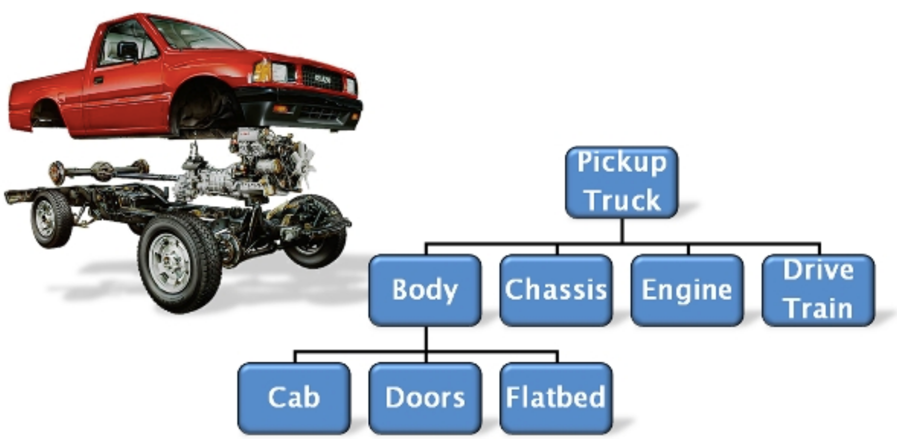
read sum
read sum
write sum + i_j
write sum + i_k

legend
thread n
thread m

  - **the update by thread m is lost!**

Collision Detection

Automaker: hierarchical 3D CAD representation of assemblies



Computing a cutaway view

```
Node *target;
std::list<Node *> output_list;
...
void walk(Node *x)  {
  switch (x->kind) {
  case Node::LEAF:
    if (target->collides_with(x))
        output_list.push_back(x);
    break;
  case Node::INTERNAL:
    for (Node::const_iterator
                child = x->begin();
                child != x->end();
                ++child)
        walk(child);
    break;
  }
}
```

Adding Cilk Plus Parallelism

Computing a cutaway view in parallel

```
Node *target;
std::list<Node *> output_list;
...
void walk(Node *x)  {
  switch (x->kind) {
  case Node::LEAF:
    if (target->collides_with(x))
        output_list.push_back(x);
    break;
  case Node::INTERNAL:
    cilk_for (Node::const_iterator
                child = x->begin();
                child != x->end();
                ++child)
        walk(child);
    break;
  }
}
```

Global variable causes data races!

Solution 1: Locking

Computing a cutaway view in parallel

```
Node *target;
std::list<Node *> output_list;
mutex m;
...
void walk(Node *x)  {
  switch (x->kind) {
  case Node::LEAF:
    if (target->collides_with(x))
    { m.lock(); output_list.push_back(x); m.unlock(); }
    break;
  case Node::INTERNAL:
    cilk_for (Node::const_iterator
              child = x->begin();
              child != x->end();
              ++child)
      walk(child);
    break;
  }
}
```

- **Add a mutex to coordinate accesses to output_list**
- **Drawback: lock contention can hurt parallelism**

Solution 2: Refactor the Code

```
Node *target;
        std::list<Node *> output_list;
        ...
        void walk(Node *x, std::list<Node *> &o_list) {
          switch (x->kind) {
          case Node::LEAF:
            if (target->collides_with(x))
                o_list.push_back(x);
            break;
          case Node::INTERNAL:
            std::vector<std::list<Node *>>
               child_list(x.num_children);
            cilk_for (Node::const_iterator
                        child = x->begin();
                        child != x->end();
                        ++child)
                walk(child, child_list[child]);
            for (int i=0; i < x.num_children; ++i)
                o_list.splice(o_list.end(), child_list[i]);
            break;
          }
```

- **Have each child accumulate results in a separate list**
- **Splice them all together**
- **Drawback: development time, debugging**

Solution 3: Cilk Plus Reducers

```
Node *target;
cilk::reducer_list_append<Node *> output_list;
    ...
    void walk(Node *x) {
      switch (x->kind) {
      case Node::LEAF:
        if (target->collides_with(x))
          output_list.push_back(x);
        break;
      case Node::INTERNAL:
        cilk_for (Node::const_iterator
                child = x->begin();
                child != x->end();
                ++child)q
          walk(child);
        break;
      }
    }
```

- **Resolve data races without locking or refactoring**
- **Parallel strands may see different views of reducer, but these views are combined into a single consistent view**

Cilk Plus Reducers

- **Reducers support update of nonlocal variables without races**
  - —deterministic update using associative operations
    - – e.g., global sum, list and output stream append, ...
    - – result using is same as serial version

      independent of # processors or scheduling
- **Can be used without significant code restructuring**
- **Can be used independently of the program's control structure**
  - — unlike constructs defined only over loops
- **Implemented efficiently with minimal overhead**
  - —they don't use locks in their implementation
    - – avoids loss of parallelism from enforcing mutual exclusion when updating shared variables

Cilk Plus Reducers Operate on Monoids

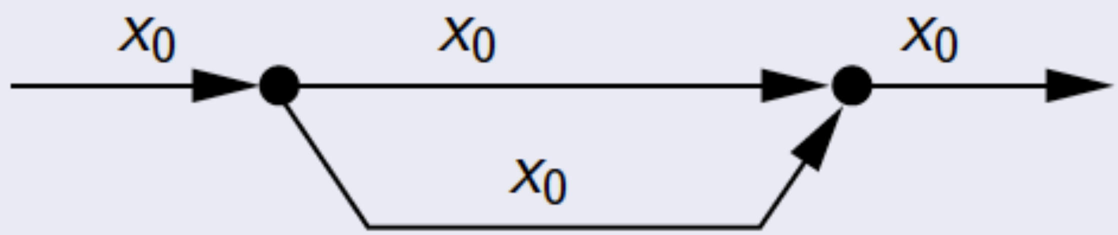
- Suppose that S is a set and • is some binary operation
  - —$S \times S \rightarrow S$
- A **monoid** is a set that is closed under an associative binary operation and has an identity element
- S with • is a monoid if it satisfies the following two axioms:
  - —identity element
    - – there exists an element I in S such that for every element a in S, the equations I • a = a • I = a hold
  - —associativity
    - – for all a, b and c in S, the equation (a • b) • c = a • (b • c) holds

Cilk++ Reducers Under the Hood

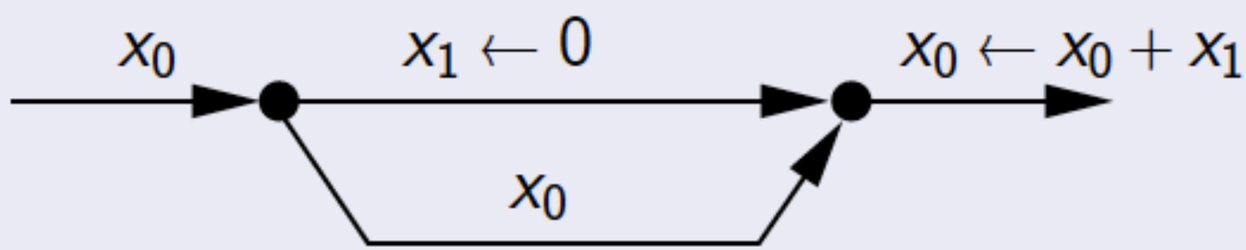
- If no steal occurs, a reducer behaves like a normal variable
- If a steal occurs
  - the continuation receives a view with an identity value
  - the child receives the reducer as it was prior to the spawn
  - at the corresponding cilk_sync
    - the value in the continuation is merged into the reducer held by the child using the reducer's `reduce` operation
    - the new view is destroyed
    - the original (updated) object survives

Reducers

Serial execution (depth first):



Parallel execution:



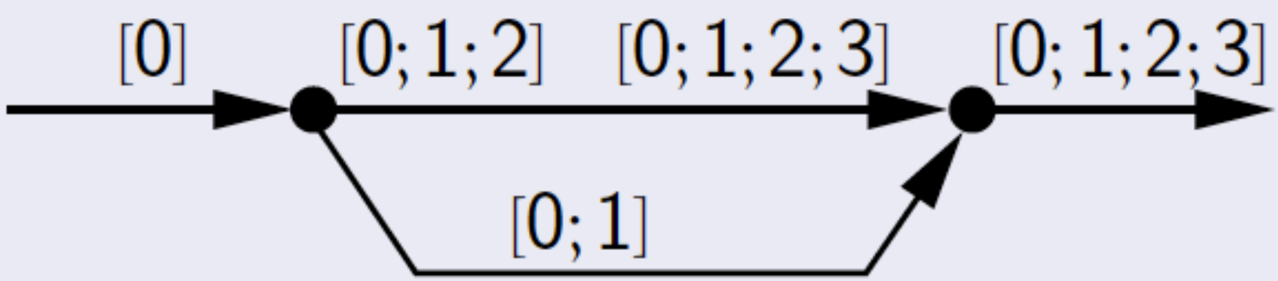
Matteo Frigo, Pablo Halpern, Charles E. Leiserson, Stephen Lewin-Berlin, Reducers and other Cilk++ hyperobjects. Slides for *SPAA'09,* August 11–13, 2009, Calgary, Alberta, Canada.

Reducing Over List Concatenation

Program:

```
x.append(0);
cilk_spawn x.append(1);
x.append(2);
x.append(3);
cilk_sync;
```

Serial execution:



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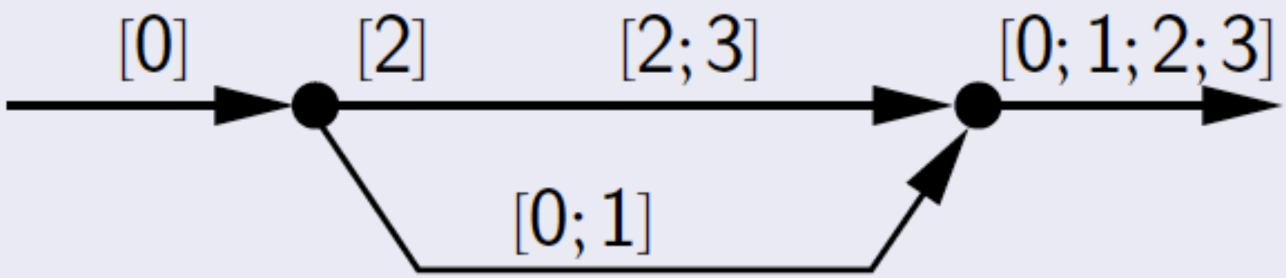

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Using Cilk Plus Reducers

- Include the appropriate Cilk Plus reducer header file

  `reducer_opadd.h`, `reducer_min.h`, `reducer_max.h`,
  `reducer_opor.h`, `reducer_opand.h`, `reducer_opxor`,
  `reducer_list.h`, `reducer_ostream.h`

- Declare a variable as a reducer rather than a standard type
  - global sum
    - `cilk::reducer_opadd<unsigned long> sum`
  - list reducer
    - instead of "`std::list<int> sequence`", use `cilk::reducer_list_append<int> sequence`

- Use reducers in the midst of work that includes parallelism created with `cilk_spawn` or `cilk_for`

- Retrieve the reducer's terminal value with `var.get_value()` after the parallel updates to the reducer are complete

Reducer Demo - I

- See /projects/comp422/cilkplus-examples/sum
- Compare a program with a racing reduction, a mutex protecting the race, and a reducer
- Versions:
  - race.cpp: code with a racing sum reduction
  - lock.cpp: code with a mutex to avoid the race
  - reducer.cpp: code with a reducer to avoid the race
- Compare performance of the various versions
  - ./race 100000000
  - ./lock 100000000
  - ./reducer 100000000
  - how does the performance of the parallel summation using reducers compare to
    - the parallel summation with races?
    - the parallel summation with locks?
    - the serial summation?

Reducer Demo - II

- **See /projects/comp422/cilkplus-examples/order/order.cpp**
- **order.cpp is a program containing two parallel loops**
  - **—one where iterations race to write output**
  - **—one where iterations write output using an ostream reducer**
- **Look at how the output differs for these loops as loop iterations are mapped to cores using work stealing**

Concurrency Cautions

- **Only limited guarantees between descendants or ancestors**
  - **—DAG precedence order maintained and nothing more**
  - **—don’t assume atomicity between different procedures!**

Race Conditions

- **Data race**
  - —two parallel strands access the same data
  - —at least one access is a write
  - —no locks held in common
- **General determinacy race**
  - —two parallel strands access the same data
  - —at least one access is a write
  - —a common lock protects both accesses

Cilkscreen

- **Detects and reports data races when program terminates**
  - —finds all data races even those by third-party or system libraries
- **Does not report determinacy races**
  - —e.g. two concurrent strands use a lock to access a queue
    - enqueue & dequeue operations could occur in different order
      potentially leads to different result

Race Detection Strategies in Cilkscreen

- **Lock covers**
  - —two conflicting accesses to a variable don’t race if some lock L is held while each of the accesses is performed by a strand
- **Access precedence**
  - —two conflicting accesses do not race if one must precede the other
    - access A is by a strand X, which precedes the cilk_spawn of strand Y which performs access B
    - access A is performed by strand X, which precedes a cilk_sync that is an ancestor of strand Y

Cilkscreen Race Example

```
#include <stdio.h>
#include "mutex.h"

long sum = 0;
mutex m;

#ifdef SYNCH
#define LOCK m.lock()
#define UNLOCK m.unlock()
#else
#define LOCK
#define UNLOCK
#endif
```

```
void do_accum(int l, int u)
{
        if (u == l) { LOCK; sum += l; UNLOCK; }
        else {
          int mid = (u+l)/2;
          cilk_spawn do_accum(l, mid);
          do_accum(mid+1, u);
        }
}
int main()
{
        do_accum(0, 1000);
        printf("sum = %d\n", sum);

        long ssum = 0;
        for (int i = 0; i <= 1000; i++) ssum +=i;
        printf("serial sum = %d\n", ssum);
}
```

note: mutex class coded using pthread_mutex lock primitives

Cilkscreen Limitations

- Only detects races between Cilk Plus strands
  - —depends upon their strict fork/join paradigm
- Only detects races that occur given the input provided
  - —does not prove the absence of races for other inputs
  - —choose your testing inputs carefully!
- Runs serially, 15-30x slower
- Increases the memory footprint of an application
  - —could cause an error if memory demand is too large
- If you build your program with debug information (compile with -g), cilkscreen will associate races with source line numbers

Cilkscreen Output

```
Cilkscreen Race Detector V2.0.0, Build 3229
summing integers from 0 to 20000

Race condition on location 0x6016f0
 write access at 0x400b7f: (/home/johnmc/examples/races/sum2.c:22, do_accum+0x169)
 read access at 0x400b78: (/home/johnmc/examples/races/sum2.c:22, do_accum+0x162)
  called by 0x400ca9: (/home/johnmc/examples/races/sum2.c:26, do_accum+0x293)
  called by 0x400c8f: (/home/johnmc/examples/races/sum2.c:25, do_accum+0x279)
  called by 0x400c8f: (/home/johnmc/examples/races/sum2.c:25, do_accum+0x279)
  ...
  called by 0x400c8f: (/home/johnmc/examples/races/sum2.c:25, do_accum+0x279)
  called by 0x400c8f: (/home/johnmc/examples/races/sum2.c:25, do_accum+0x279)
  called by 0x400e47: (/home/johnmc/examples/races/sum2.c:37, main+0x85)

Race condition on location 0x6016f0
 write access at 0x400b7f: (/home/johnmc/examples/races/sum2.c:22, do_accum+0x169)
 write access at 0x400b7f: (/home/johnmc/examples/races/sum2.c:22, do_accum+0x169)
  called by 0x400ca9: (/home/johnmc/examples/races/sum2.c:26, do_accum+0x293)
  called by 0x400c8f: (/home/johnmc/examples/races/sum2.c:25, do_accum+0x279)
  called by 0x400c8f: (/home/johnmc/examples/races/sum2.c:25, do_accum+0x279)
  ...
  called by 0x400c8f: (/home/johnmc/examples/races/sum2.c:25, do_accum+0x279)
  called by 0x400c8f: (/home/johnmc/examples/races/sum2.c:25, do_accum+0x279)
  called by 0x400e47: (/home/johnmc/examples/races/sum2.c:37, main+0x85)

sum = 200010000
serial sum = 200010000
2 errors found by Cilkscreen
Cilkscreen suppressed 119998 duplicate error messages
```

cilkscreen Demo

- **Explore cilkscreen race detection**
  - `cp /projects/comp422/cilkplus-examples/races ~/races`
  - `cd ~/races`
  - `programs:`
    - `race.c -`

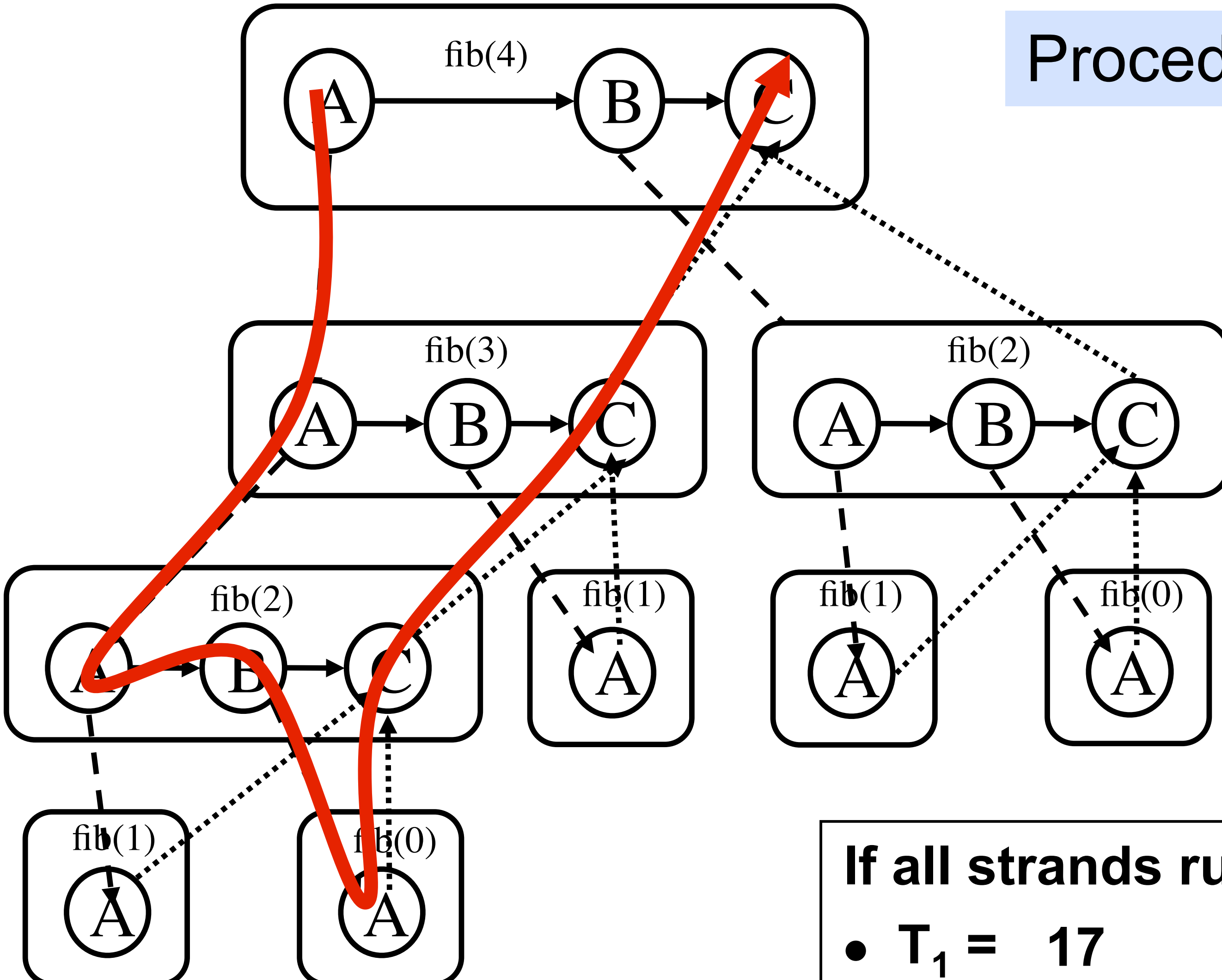
      `a cilk_for summation with a race`

      `race can be suppressed with -DSYNCH using a mutex)`
    - `race2.c - a task parallel summation w/ optional mutex`

Performance Measures

- T_s = serial execution time
- T_1 = execution time on 1 processor (total work), $T_1 \geq T_s$
- T_p = execution time on P processors
- T_∞ = execution time on infinite number of processors
  - longest path in DAG
    - length reflects the cost of computation at nodes along the path
  - known as "critical path length"

Work and Critical Path Example



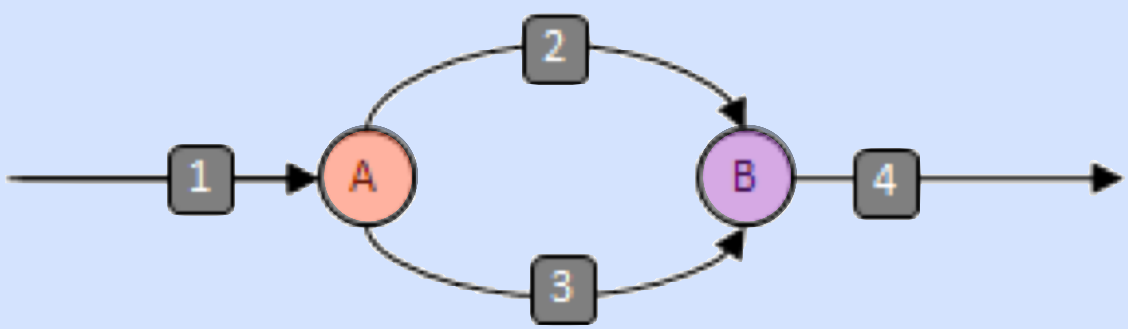
Procedure oriented view

If all strands run in unit time

- **T_1 = 17**
- **T_∞ = 8 (critical path length)**

Execution DAG View

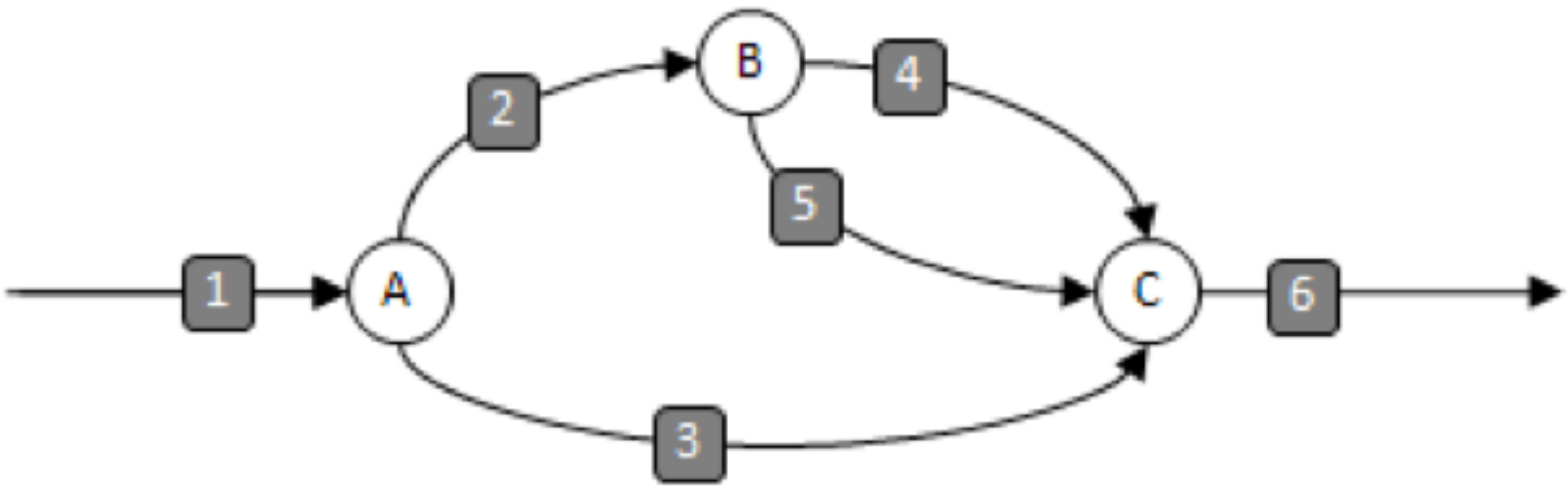
- Cilk Plus uses the word “strand” for a serial section of the program
- A “knot” is a point where three or more strands meet
- Two kinds of knots
  - spawn knots: one input strand, two output strands
  - sync knots: two or more input strands, one output strand




```
...
do_stuff1();
cilk_spawn func3();
do_stuff2();
cilk_sync;
do_stuff4();
...
```

Another Execution DAG

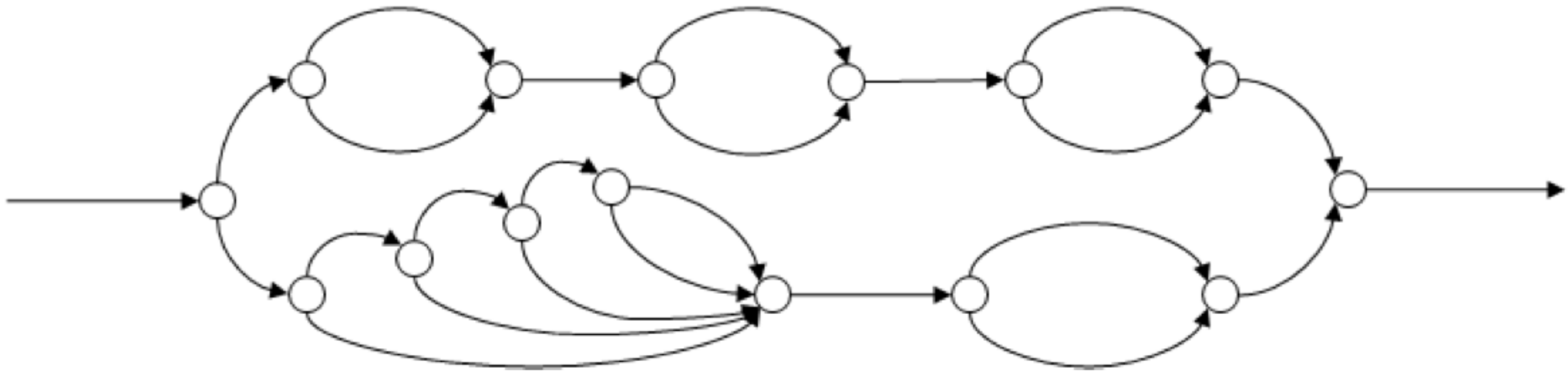
- **DAG represents the series-parallel structure of the execution of a Cilk Plus program**
- **Example:**
  - **two spawns (A) & (B)**
  - **one sync (C)**



Note: computation on edges

Work and Span

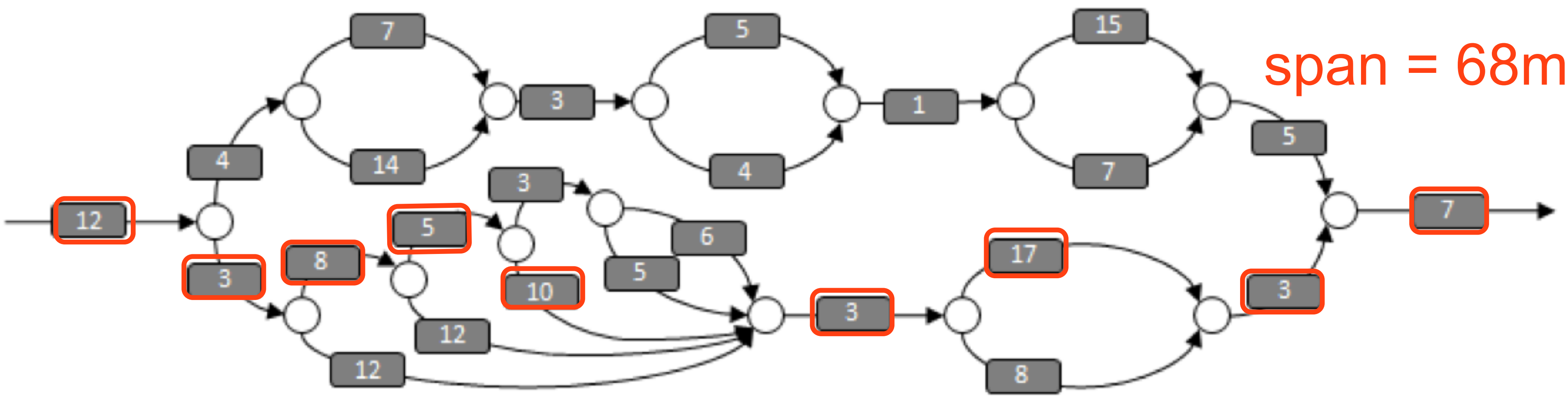
- **Edges represent serial computation (work)**



- **Span: most expensive path from beginning to end**
  - also known as critical path length

work = 181ms

span = 68ms



Note: computation on edges

cilkview

- **Rewrites executable to measure execution in terms of work and span**
  - **measures**
    - **work - total # instructions executed, w/o parallel ovhd**
    - **span - # instructions executed on the critical path (w/o ovhd)**
    - **burdened span - # instructions executed on critical path (incl ovhd)**
    - **parallelism - work/span (max speedup on infinite cores, w/o ovhd)**
    - **burdened parallelism - work/(burdened span)**
    - **number of spawns/syncs**
    - **average instructions per strand - work/strands**
    - **strands along span - # strands in the critical path**
    - **average instructions / strand on span = work/(strands along span)**
    - **total number of atomic instructions - e.g., used for locks**
    - **frame count**
- **Predicts speedup on various numbers of processors based on work and span**

cilkview Demo

- **Explore cilkview for performance analysis using fib example `/projects/comp422/cilkplus-examples/fib`**
  - `cilkview ./fib 20`
  - `cilkview ./fib 30`
  - `cilkview ./fib 35`
  - `cilkview ./fib-trunc 35 10`

Cilk Plus Array Notation

- **Elementwise arithmetic**

```
c[:] = a[:] + 5;
```

- **Set even rows in a 2D array**

```
b[0:5:2][:] = 12;
```

- **Vector conditionals**

```
// Check and report each element containing 5 w/ Array Notation
if (5 == a[:]) an_results[:] = "Matched";
else an_results[:] = "Not Matched";
```

- **Applying a scalar function to elements in a vector**

```
// Call a fn on each element of a vector using Array Notation
fn(a[:]);
```

`See /projects/comp422/cilkplus-features-tutorial`

More Cilk Plus Features

- See /projects/comp422/cilkplus-features-tutorial
  - —array_notations: vector notation in Cilk Plus
  - —reducers: more reducer examples
- Each directory contains a Makefile that can build and run all examples

Recall: Task Scheduling in Cilk

Strategies

- **Work-stealing: processor looks for work when it becomes idle**
- **Lazy parallelism: don't realize parallelism until necessary**
  - **benefits:**
    - **executes with precisely as much parallelism as needed**
    - **minimizes the number of threads that must be set up**
    - **runs with same efficiency as serial program on uniprocessor**

Compilation Strategy

MIT Cilk generates two copies of each procedure

- **Fast clone: for optimized execution on a single processor**
  —spawned threads are fast
- **Slow clone: triggered by work stealing, full parallel support**
  —used to handle execution of “stolen procedure frames”
  —supports Cilk’s work-stealing scheduler
  —few steals when enough parallel slackness exists
    – speed of slow copy is not critical for performance
- **“Work-first” principle: minimize cost in fast clone**

Two Schedulers

- **Nanoscheduler: compiled into cilk program**
  - —execute cilk function and spawns in exactly the same order as C
  - —on one PE: when no microscheduling needed, same order as C
  - —efficient coordination with microscheduler
- **Microscheduler**
  - —schedule procedures across a fixed set of processors
  - —implementation: randomized work-stealing scheduler
    - – when a processor runs out of work, it becomes a thief
    - – steals from victim processor chosen uniformly at random

Nanscheduler Sketch

- Upon entering a cilk function
  - allocate a frame in the heap
  - initialize frame to hold function's state
  - push the frame on the bottom of a deque
    - frame on stack ↔ frame in deque
- At a spawn
  - save function state into the frame
    - only live, dirty variables
  - save the entry number into the frame
  - call spawned procedure as a function
- After each spawn
  - check to see if if parent has been stolen
    - if frame is still in the deque, it has not
  - if so, clean up C stack
- Each sync becomes a no-op
- When the procedure returns

Fast clone

```
int fib (int n)
{
    fib_frame *f;                       frame pointer
    f = alloc(sizeof(*f));              allocate frame
    f->sig = fib_sig;                   initialize frame
    if (n<2) {
        free(f, sizeof(*f));            free frame
        return n;
    }
    else {
        int x, y;
        f->entry = 1;                   save PC
        f->n = n;                       save live vars
        *T = f;                         store frame pointer
        push();                         push frame
        x = fib (n-1);                  do C call
        if (pop(x) == FAILURE)          pop frame
            return 0;                   frame stolen
        ...                             second spawn
        ;                               sync is free!
        free(f, sizeof(*f));            free frame
        return (x+y);
    }
}
```

Fast Clone and Nanoscheduler

- Fast clone is never stolen
  - —converted to slow when steal occurs
  - —enables optimizations
- No sync needed in fast clone
  - —no children have been spawned
- Frame saves state:
  - —PC (entry number)
  - —live, dirty variables
- Push and pop must be fast

Nanoscheduler Overheads

Basis for comparison: serial C

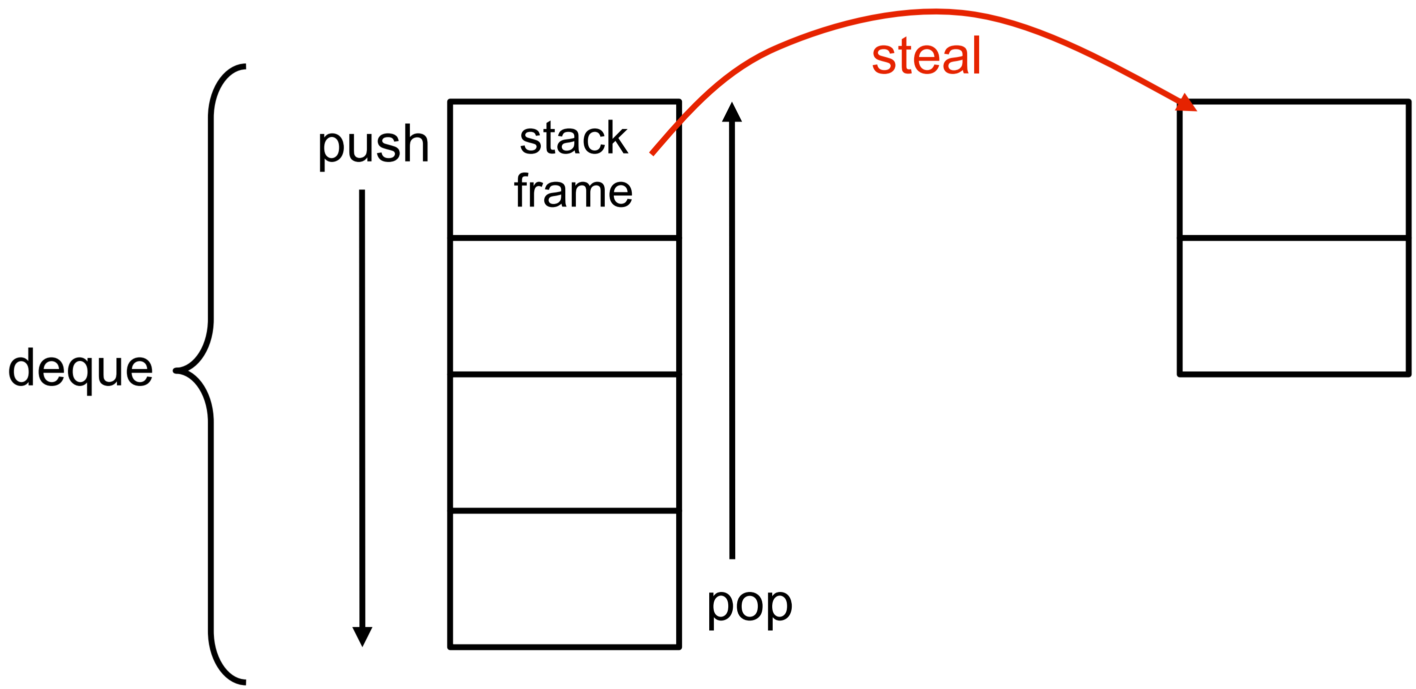
- Allocation and initialization of frame, push onto ‘stack’
  - a few assembly instructions
- Procedure’s state needs to be saved before each spawn
  - entry number, live variables
- Check whether frame is stolen after each spawn
  - two reads, compare, branch
- On return, free frame - a few instructions
- One extra variable to hold frame pointer

Runtime Support for Scheduling

Each processor has a ready deque (doubly ended queue)

- Tail: worker adds or removes procedures (like C call stack)
- Head: thief steals from head of a victim's deque

Deque for a Process



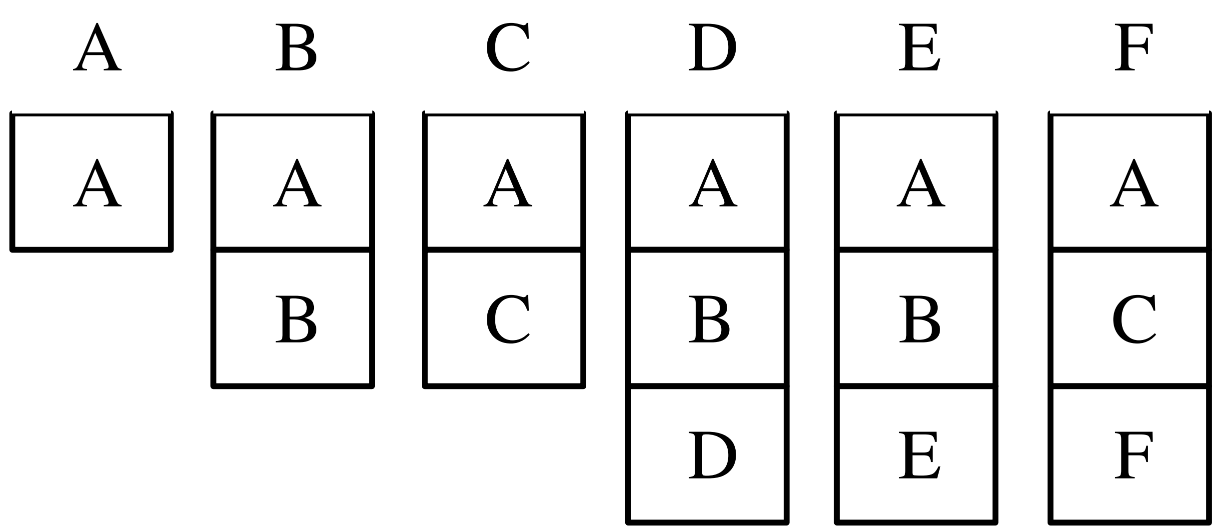
- ***Deque* grows downward**
- ***Stack frame* contains local variables for a procedure invocation**
  - **Procedure call → new frame is pushed onto the bottom of the deque**
  - **Procedure return → bottom frame is popped from the deque**

Cilk's Cactus Stacks

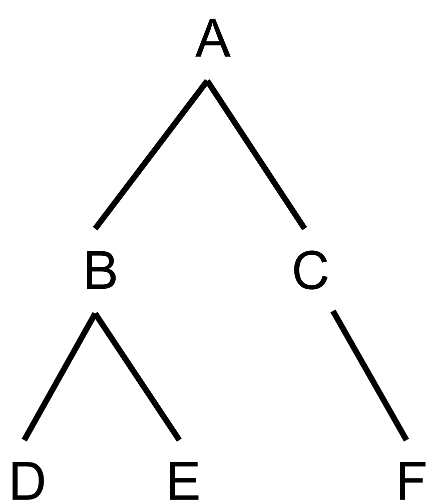
A cactus stack enables sharing of a C function's local variables

```
void A() { B(); C(); }
void B() { D(); E(); }
void C() { F(); }
void D() {}
void E() {}
void F() {}
```

each procedure's view of stack



call tree



Rules

- —**pointers can be passed down call chain**
- —**only pass pointers up if they point to heap**
  - **functions <u>cannot</u> return ptrs to local variables**

Microscheduler

Schedule procedures across a fixed set of processors

- **When a processor runs out of work, it becomes a thief**
  - steals from victim processor chosen uniformly at random
- **When it finds victim with frames in its deque**
  - takes the topmost frame (least recently pushed)
  - places frame into its own deque
  - gives the corresponding procedure to its own nanoscheduler
- **Microscheduler executes slow clone**
  - receives only pointer to frame as argument
    - real args and local state in frame
  - restores pgm counter to proper place using switch stmt (Duff's device)
  - at a sync, must wait for children
  - before the procedure returns, place return value into frame

Coordinating Thief and Worker

Options

- **Always use a lock to manipulate each worker's deque**
- **Use protocol that only relies on atomicity of read and write**
  - **based on ideas from a locking protocol by Dijkstra**

Simplified THE Protocol (Without the ‘E’)

- **Shared memory deque**
  - T: first unused
  - H: head
  - E: exception
- **Work-first**
  - move costs from worker to thief
- **One worker per deque**
- **One thief at a time**
  - enforced by lock

Worker/Victim

```
push() {
  T++;
}

pop() {
  T--;
  if (H > T) {
    T++;
    lock(L);
    T--;
    if (H > T) {
      T++;
      unlock(L);
      return FAILURE;
    }
    unlock(L);
  }
  return SUCCESS;
}
```

Thief

```
steal() {
  lock(L);
  H++;
  if (H > T) {
    H--;
    unlock(L);
    return FAILURE;
  }
  unlock(L);
  return SUCCESS;
}
```

- actions on tail contribute to work overhead
- actions on head contribute only to critical path overhead

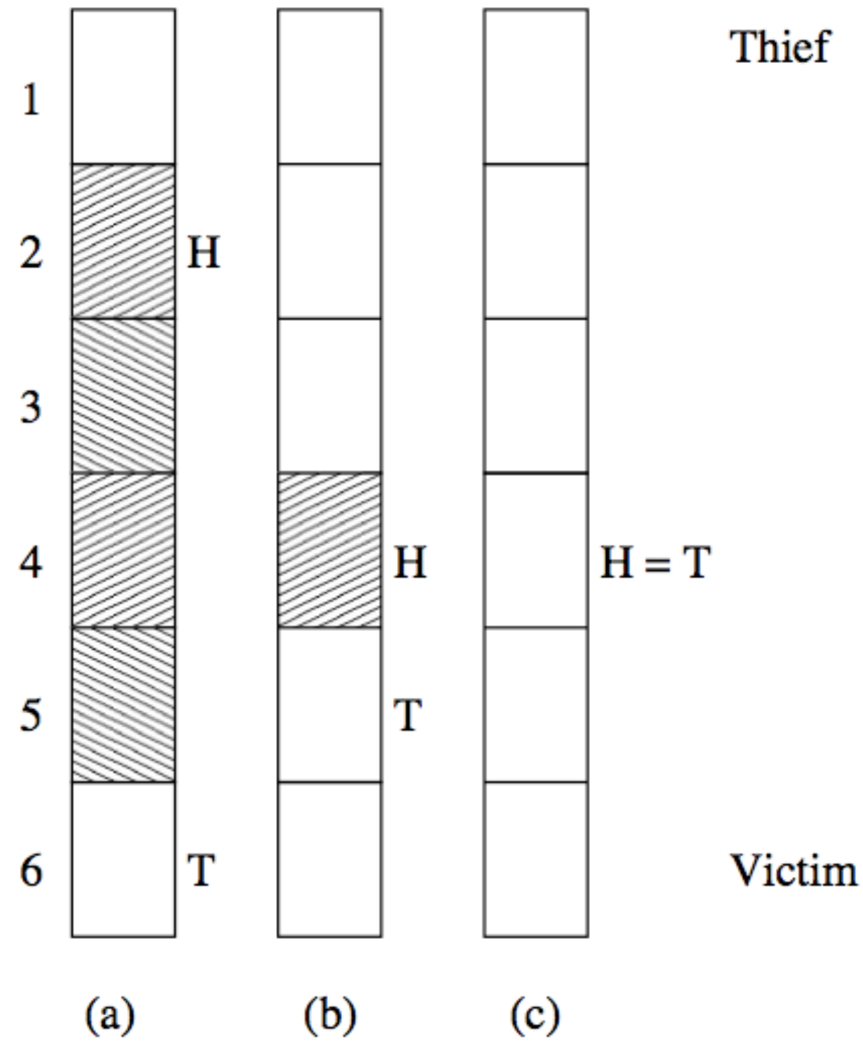
Deque Pop

Three cases

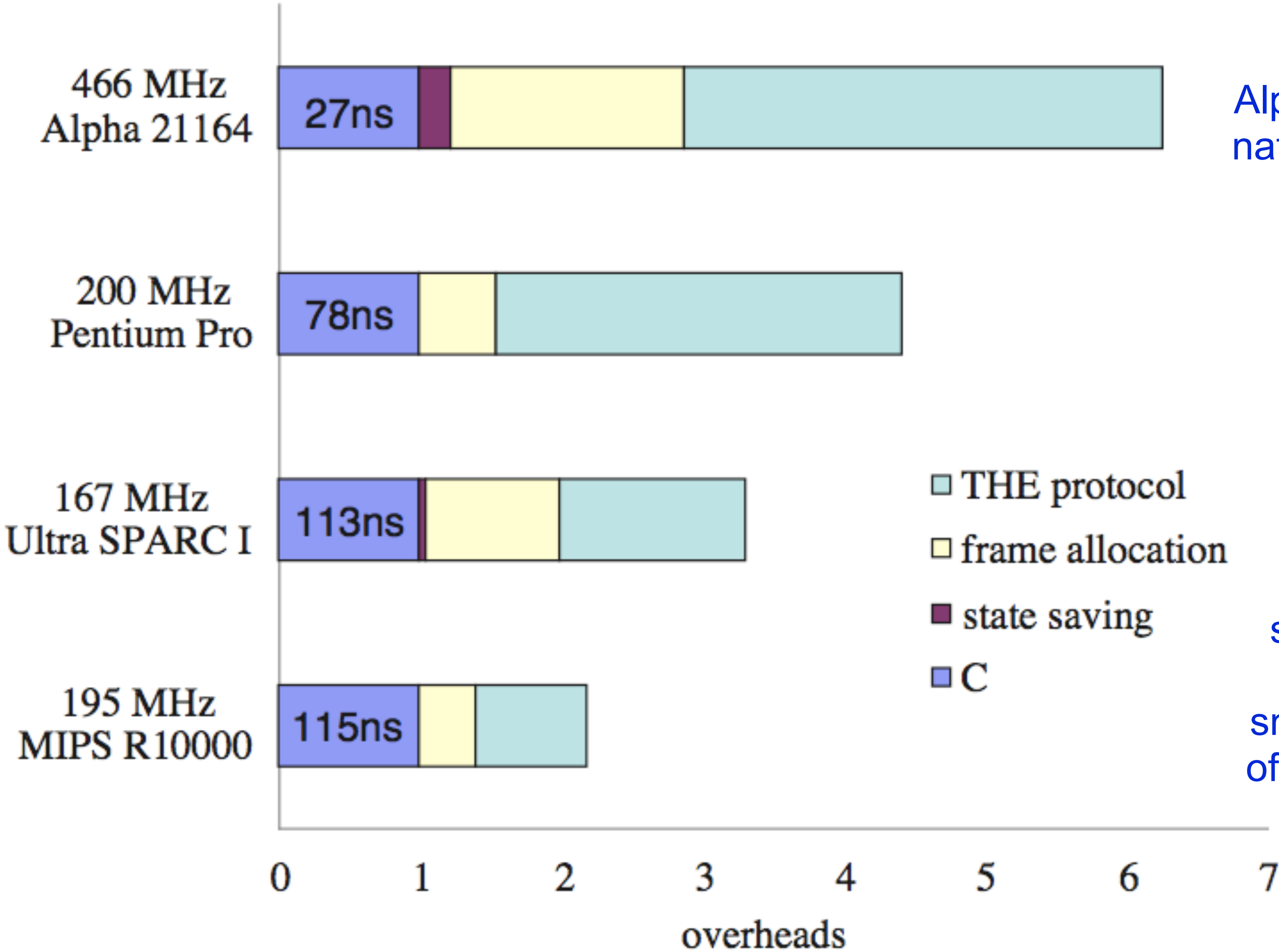
(a) **no conflict**

(b) At least one (thief or victim) finds (H > T) and backs up; other succeeds

(c) Deque is empty, both threads return



Work Overhead for `fib`



Alpha has fast native function calls

state saving overhead small because of write buffers

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