Cilk Multithreaded Language

Introduction and implementation

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Outline

- Introduction
- The Cilk Language
- Work-first principle
- Cilk compiler
- Work Stealing
- Evaluations
- Cilk++ - Hyperobjects
- Summary

Introduction

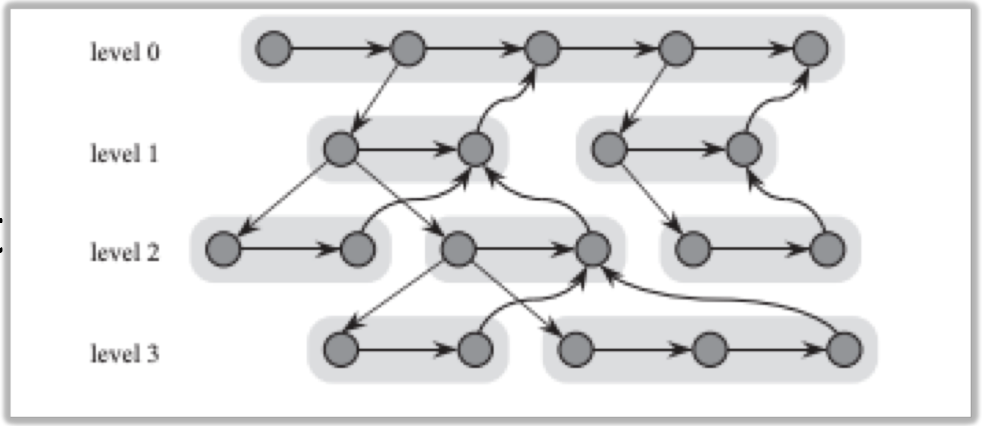
- General purpose programming language for *multi-threaded* computing.
- Designed at MIT in 1990's (Cilk-1 launched in 1994)
- Generalizes semantics of C language.
- Cilk Scheduler gives guarantee of application performance- *Work Stealing!*
- Performance measures – *Work* and *Critical Path*

Silk threads!
Source: Encyclopedia Britannica

https://www.cilkplus.org/cilk-history

Introduction

- Represented as a DAG. Collection of Cilk procedures and sequence of threads
- Each thread is non-blocking.
- Threads are required to spawn successor that can accept values from children.
- Thread receiving value can't begin until another thread sends value – Dependency
- Execution is constrained to follow precedence relation determined by DAG.



Blumfoe R. et al, *PPoPP* (1995)

The Cilk Language

- Philosophy- make Cilk a true parallel extension of C
  - On a parallel computer, Cilk control constructs allow the program to execute parallelly
  - If Cilk keywords are elided- C elision
- On a uniprocessor – Cilk *nearly* as fast as C.
- Performance characterization measures
  - Work - Time used by one processor execution (T_1)
  - Critical Path – Time required for execution by an infinite processor (T_∞)
  - For *P* processors – $T_P \geq T_1/P$
- Follows the Work First principle
  - ***"Minimize scheduling overhead borne by the work of a computation. Move overheads out of work and onto the critical path"***

The Cilk Language

- Work-first principle – strategy for compilation
  - Cilk2c compiler – transforms a Cilk source to a C postsource
  - C post source run through a gcc compiler
  - Two clones – “fast clone” and “slow clone”
- Communication due to scheduling occurs in the slow clone and contributes to the critical-path overhead.
- Work-first principle – Mutual exclusion and load-balancing scheduler
- ”Thieves” and “victims” – Idle-processor steal threads from busy processors. Guarantees overhead contributes only to critical-path
- Minimize work overhead – Dijkstra-like mutual exclusion (**THE**)

The Cilk Language

- Cilk-5

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

cilk int fib (int n)
{
    if (n<2) return n;
    else {
        int x, y;
        x = spawn fib (n-1);
        y = spawn fib (n-2);
        sync;
        return (x+y);
    }
}

cilk int main (int argc, char *argv[])
{
    int n, result;
    n = atoi(argv[1]);
    result = spawn fib(n);
    sync;
    printf ("Result: %d\n", result);
    return 0;
}
```

```
cilk int fib (int n)
{
    int x = 0;
    inlet void summer (int result)
    {
        x += result;
        return;
    }

    if (n<2) return n;
    else {
        summer(spawn fib (n-1));
        summer(spawn fib (n-2));
        sync;
        return (x);
    }
}
```

Cilk Plus Terminology

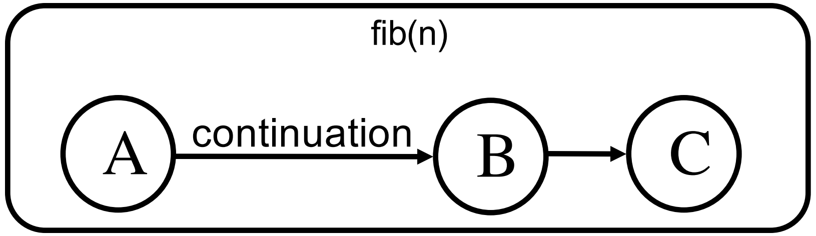
- **Parallel control**
  - —**cilk_spawn, cilk_sync**
  - —**return from spawned function**
- **Strand**
  - —**maximal sequence of instructions not containing parallel control**

```
unsigned int fib(n)  {
  if (n < 2) return n;
  else {
    unsigned int n1, n2;
    n1 = cilk_spawn fib(n - 1);
    n2 = cilk_spawn fib(n - 2);
    cilk_sync;
   return (n1 + n2);
  }
}
```

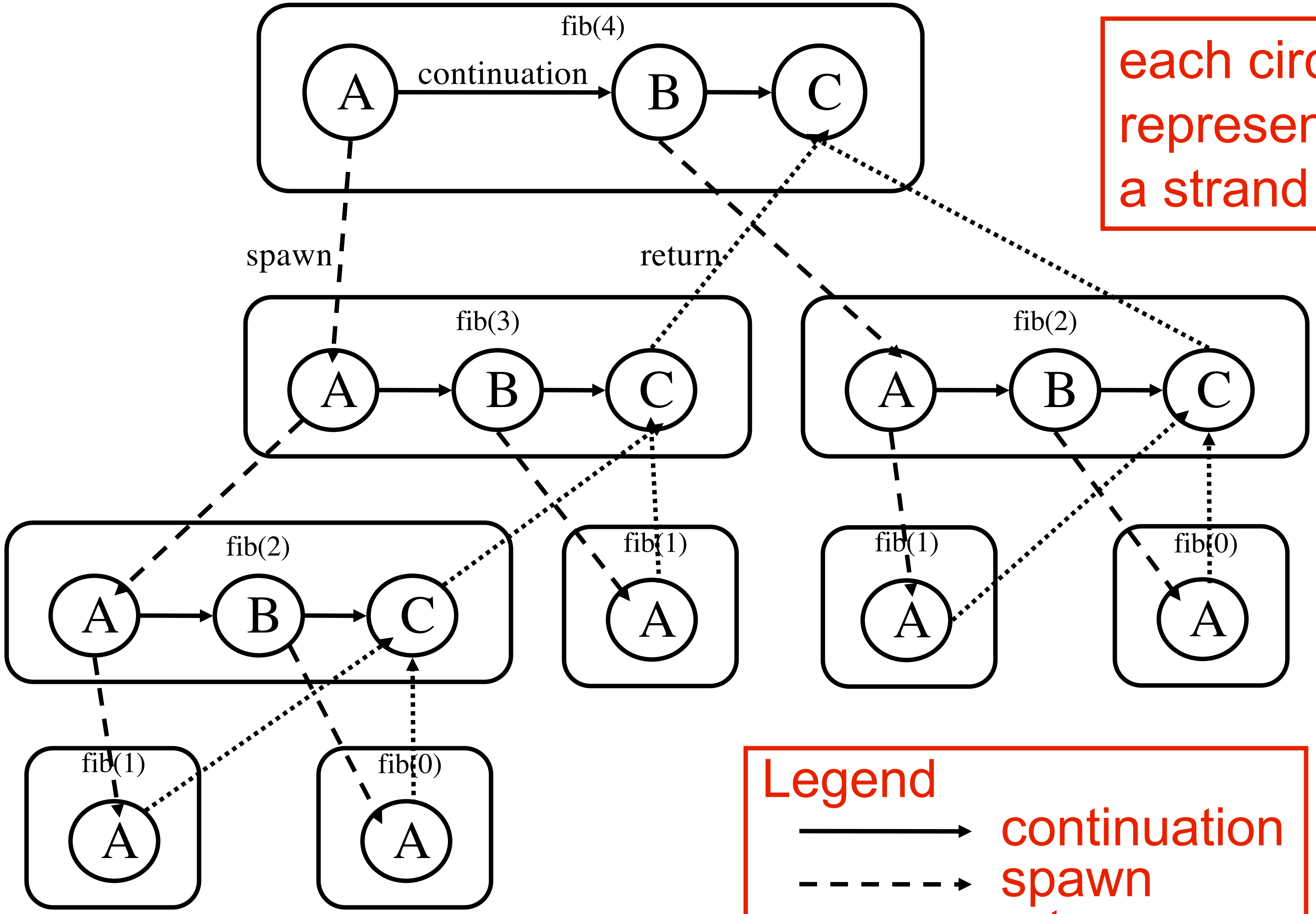
Strand A: code before first spawn

Strand B: compute n-2 before 2nd spawn

Strand C: n1+ n2 before the return



Cilk Program Execution as a DAG



each circle represents a strand

Legend
continuation
spawn
return

The Cilk Language

- Cilk-5

```
cilk int fib (int n)
{
    int x = 0;
    inlet void summer (int result)
    {
        x += result;
        return;
    }

    if (n<2) return n;
    else {
        summer(spawn fib (n-1));
        summer(spawn fib (n-2));
        sync;
        return (x);
    }
}
```

- Inlets - C function internal to Cilk
  - In normal Cilk syntax – spawning cannot be linked to a statement
  - Inlets can call spawn as an argument.
  - Control of the parent procedure shifts to the statement after the inlet call.
  - Returned result added to x within inlet.
  - Cilk provides atomicity implicitly among threads so updates aren’t lost.
  - Don’t spawn from an inlet!
  - x += spawn fib(n-1)

The Cilk Language

- Cilk-5

```
cilk int fib (int n)
{
    int x = 0;
    inlet void summer (int result)
    {
        x += result;
        return;
    }

    if (n<2) return n;
    else {
        summer(spawn fib (n-1));
        summer(spawn fib (n-2));
        sync;
        return (x);
    }
}
```

- Abort - ”Speculative work” can be aborted inside an inlet.
- Think parallel searches!
- When executed inside the inlet all the spawned children of the procedure automatically terminate.
- Authors considered using other synchronizing techniques but critical path cost too high.
- Sync - useful for systems that support relaxed memory-consistency model.
- Cilk programmers can also use additional locking for mutual exclusion – Future work

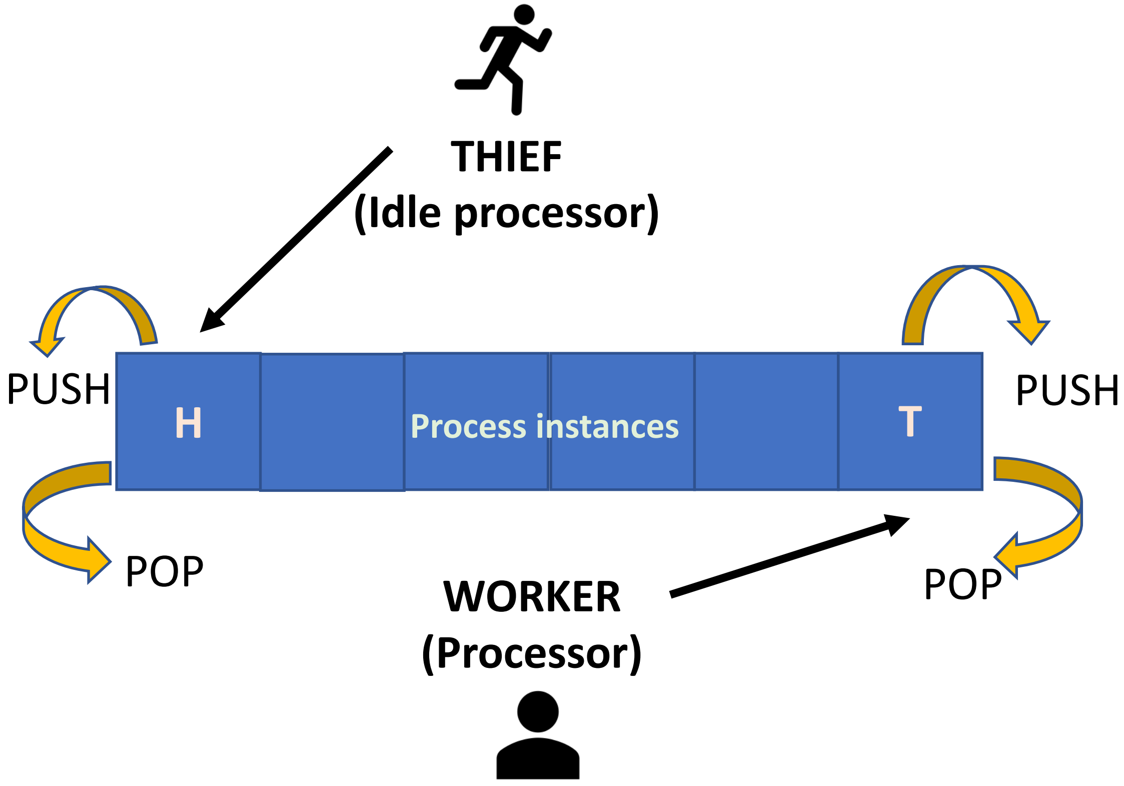
Work-first principle

- Three assumptions for work-first principle:
  - Cilk scheduler operates in practice according to the theoretical analysis
  - Ample ”Parallel slackness” (enough parallel work to keep all threads busy)
  - Every Cilk program has a C elision against which its one-processor performance is measured
- Two fundamental lower bounds must hold:
  - $T_P \geq T_1/P$
  - $T_P \geq T_\infty$
- Cilk’s randomized work-stealing scheduler executes a Cilk computation on P processors in expected time
  - $T_P = T_1/P + O(T_\infty)$ ----[Eqn 1.]
  - This equation is optimal within a constant factor since RHS are both lower bounds.

Work-first principle

- The first term in equation 1 – work term and the second term is the critical path term.
- Modifying Eqn 1 to make overheads explicit:
  - $T_P \leq T_1/P + c_\infty T_\infty$ ----[Eqn 2.]
  - Define smallest constant c_∞ as the critical-path overhead.
- Terms relevant to second assumption
  - Average parallelism $\overline{P} = T_1 / T_\infty$
  - Parallel slackness $\overline{P} / P$ (assumption. >> c_∞)
  - From Equation 2 we have, $T_1 / P >> c_\infty T_\infty$; $T_P \cong T_1/P$
- Third assumption
  - $C_1 = T_1 / T_S$
  - $T_P \leq c_1 T_S/P + c_\infty T_\infty$; $c_1 T_S / P$ [**Minimize C_1 even at the expense of larger C_∞!**]

Cilk's compilation strategy



- Cilk scheduling
  - Worker maintains ready deque of ready procedures.
  - Worker operates on it tail- C call stack
  - Thief attempts to steal procedure; worker becomes a victim.
  - Thief grabs procedures from the head of the deque
  - When spawned fast clone runs and as soon as thief steals procedure converted to slow clone

Cilk's compilation strategy

```
1   int fib (int n)
2   {
3       fib_frame *f;                    frame pointer
4       f = alloc(sizeof(*f));           allocate frame
5       f->sig = fib_sig;                initialize frame
6       if (n<2) {
7           free(f, sizeof(*f));         free frame
8           return n;
9       }
10      else {
11          int x, y;
12          f->entry = 1;                save PC
13          f->n = n;                    save live vars
14          *T = f;                      store frame pointer
15          push();                      push frame
16          x = fib (n-1);               do C call
17          if (pop(x) == FAILURE)       pop frame
18              return 0;                frame stolen
19          ...                          second spawn
20          ;                            sync is free!
21          free(f, sizeof(*f));         free frame
22          return (x+y);
23      }
24  }
```

- Cilk2c
  - Lines 4 and 5 represent the activation frame for *fib*. Frame initialized in 5 by storing static structure.
  - First spawn [Lines 12 – 18]
    - Lines 12-13 state of fib is saved onto the activation frame.
    - Lines 14-15 the frame is pushed on to the runtime deque.
    - Line 16 C call to function
    - Lines 17-18 check to whether parent procedure was stolen.

Cilk's compilation strategy

```
1   int fib (int n)
2   {
3       fib_frame *f;                  frame pointer
4       f = alloc(sizeof(*f));         allocate frame
5       f->sig = fib_sig;              initialize frame
6       if (n<2) {
7           free(f, sizeof(*f));       free frame
8           return n;
9       }
10      else {
11          int x, y;
12          f->entry = 1;              save PC
13          f->n = n;                  save live vars
14          *T = f;                    store frame pointer
15          push();                    push frame
16          x = fib (n-1);             do C call
17          if (pop(x) == FAILURE)     pop frame
18              return 0;              frame stolen
19          ...                        second spawn
20          ;                          sync is free!
21          free(f, sizeof(*f));       free frame
22          return (x+y);
23      }
24  }
```

- Cilk2c
  - In a fast clone all sync statements compile to no-ops.
  - Line 20, sync is empty! Line 21-22 fib deallocates the frame and returns to parent procedure.
  - Slow clone – when a procedure is stolen control has been suspended between spawn or sync points
  - Goto statement used to restore program counter after slow cone resumes.

Cilk's compilation strategy

- Cilk2c runtime linkage
  - Sync in slow clone – cilk2c inserts a call to runtime system which checks for spawned children
  - Parallel book-keeping is minimum as:
    - No contribution to *work*
    - Stealing guaranteed to be minimum
  - Separation between fast clones and slow clones allows efficient compilation of inlets and abort
  - Implicit inlet calls compile directly to C elision. An abort statement, similar to sync, is a no-op.

```
cilk int fib (int n)
{
    int x = 0;
    inlet void summer (int result)
    {
        x += result;
        return;
    }

    if (n<2) return n;
    else {
        summer(spawn fib (n-1));
        summer(spawn fib (n-2));
        sync;
        return (x);
    }
}
```

```
tmp = spawn fib(n-1);
summer(tmp);
```

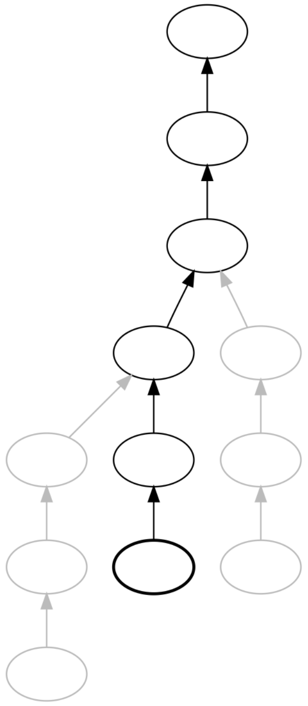
Cilk's compilation strategy

- Runtime system tethers fast and slow clones
  - Includes protocols for stealing procedures, returning values between processors, executing inlets and aborting computation subtrees.
  - All costs amortized against critical path
- What's the work overhead ?
  - Stealing protocol executed by the worker
  - Allocating and freeing of activation frame, saving state before a spawn and checking if a procedure is stolen or not.
  - A small portion of this overhead is due to Cilk compiler duplicating the work done by the C compiler –overhead is small!

Cilk's compilation strategy

- Allocating activation frames is an important step during Cilk2c operation
  - Cilk-4: Stack-based allocation
  - Cilk-5: Heap-based allocation

- So, Stack or Heap ?
  - 'Cactus Stack' – Cilk-4 had to manage the virtual-memory map on each processor explicitly.
  - Overhead due to page fault in critical sections lead to complicated protocols- an expensive user-level interrupt during which memory map is modified



Cactus Stack or a Spaghetti Stac

Source: Wiki/Parent-pointer-tree

Cilk's compilation strategy

Critical path is a concern!

- These overheads could be moved on to the critical path
- But in practice it overburdens the critical path and violates the assumption of parallel slackness
- One-processor execution – fast but insufficient slackness sometimes resulted in poor parallel performance.

Cilk-5 has a Heap

- Frame allocated off a free list and deallocation requires frame to be pushed into free list. Heap allocation only slightly more expensive.
- Heap has a disadvantage- potentially waste a lot more memory because of fragmentation of memory.

Cilk's compilation strategy

- Carefully evaluate critical-path overheads.
  - Can tip the scales where underlying parallel slackness assumption will not hold.
- Cilk-5 overhead believed to be optimal.
  - Portability vs performance tradeoff
- Lazy threads obtains better efficiency
  - Implementing its own calling conventions, stack layouts etc.

Work Stealing

- Work-stealing mechanism called “**THE**” protocol.
- Implementations:
  - Thief interrupts a worker and demand attention from this victim.
  - Post steal requests and workers could periodically poll them.
- Possible data-race between Thief and Victim- steal the same frame victim is trying to pop!
- One possible solution: add lock to deque
- Adopt a solution similar to mutual exclusion where only reads and writes are atomic!

Work Stealing

- "THE":
  - 3 atomic variables, **T,H,E**
  - Aim to move costs from the worker to the thief
  - Many thieves and one victim- need a hardware lock
  - Worker and a sole thief- can use mutual exclusion with little work overhead.
- Pseudocode:
  - T,H stored in shared memory and visible to all processors.
  - Worker treats deque as a stack
    - Before spawn: push frame to tail
    - After spawn: pop frame

Worker/Victim

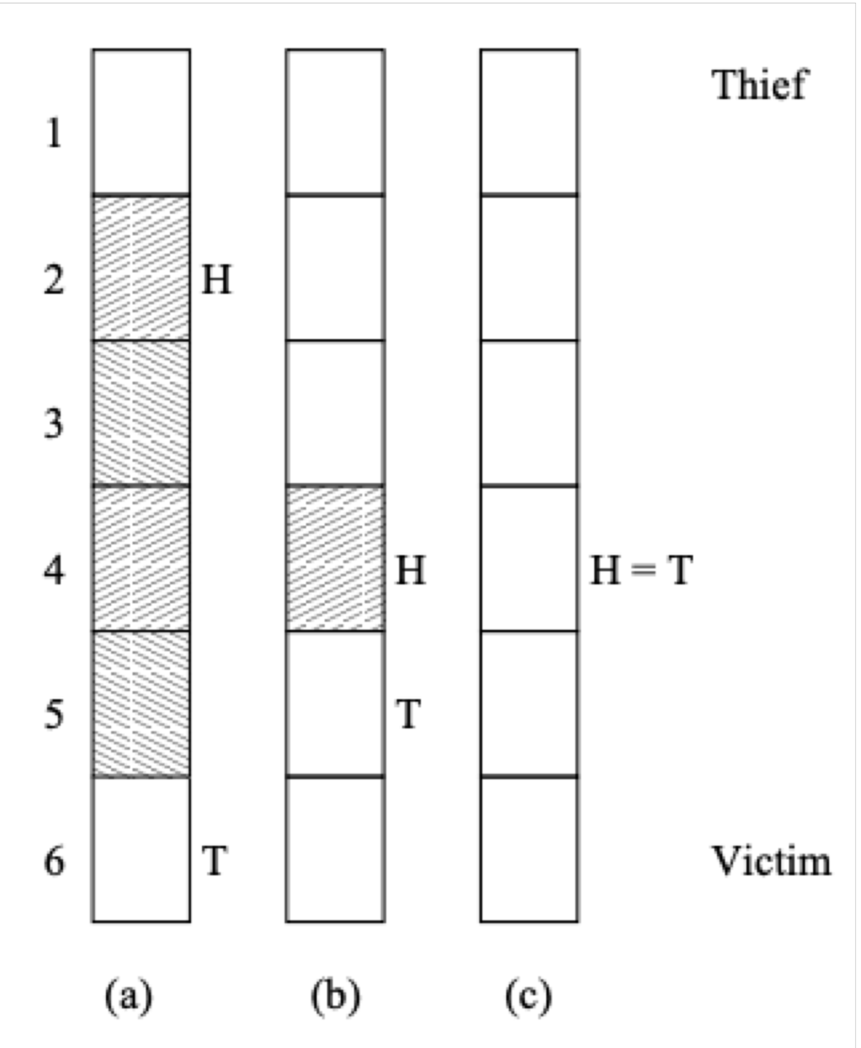
```
push() {
  T++;
}

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;
}
```

Work Stealing

- Always safe to push onto deque!
- Case (a) - enough frames available for thief and worker
- Case (b) - only one frame – data race condition!
- Case (c) – deque empty. Pop fails and steal fails! Will there be a deadlock?
- No significant overhead – Push just updates T and pop takes 6 operations. Expensive lock on theft- depends on T_∞, can be considered critical path.



Work Stealing

- Performance:
  - Compared to pop with lock - THE performs 25% faster in UltraSPARC –I. Requires membar between lines 5 and 6.
  - On Pentium Pro- THE is only 5% faster, spends about half of its time in this memory fence
- "Non-blocking" THE has advantages:
  - Less prone to problems arising out of spin lock
  - The infrequency of locking means that a thief can usually complete a steal operation on the workers deque.

Worker/Victim

```
1   push() {
2     T++;
3   }

4   pop() {
5     T--;
6     if (H > T) {
7       T++;
8       lock(L);
9       T--;
10      if (H > T) {
11        T++;
12        unlock(L);
13        return FAILURE;
14      }
15      unlock(L);
16    }
17    return SUCCESS;
18  }
```

Thief

```
1   steal() {
2     lock(L);
3     H++;
4     if (H > T) {
5       H--;
6       unlock(L);
7       return FAILURE;
8     }
9     unlock(L);
10    return SUCCESS;
11  }
```

Work Stealing

- Introducing **E:**
  - Simplified model can be extended to incorporate communication.
  - In the simplified version, H marks head of deque and marks points that victim can't cross.
  - Now, E marks this point and E > T asserted in line 6
  - Lines 7 to 15 are replaced by a call to an exception handler.
  - Before stealing, thief increments E. If stolen, increment H, else, restore E.
  - Exception mechanism executes abort

Worker/Victim

```
1   push() {
2     T++;
3   }

4   pop() {
5     T--;
6     if (H > T) {
7       T++;
8       lock(L);
9       T--;
10      if (H > T) {
11        T++;
12        unlock(L);
13        return FAILURE;
14      }
15      unlock(L);
16    }
17    return SUCCESS;
18  }
```

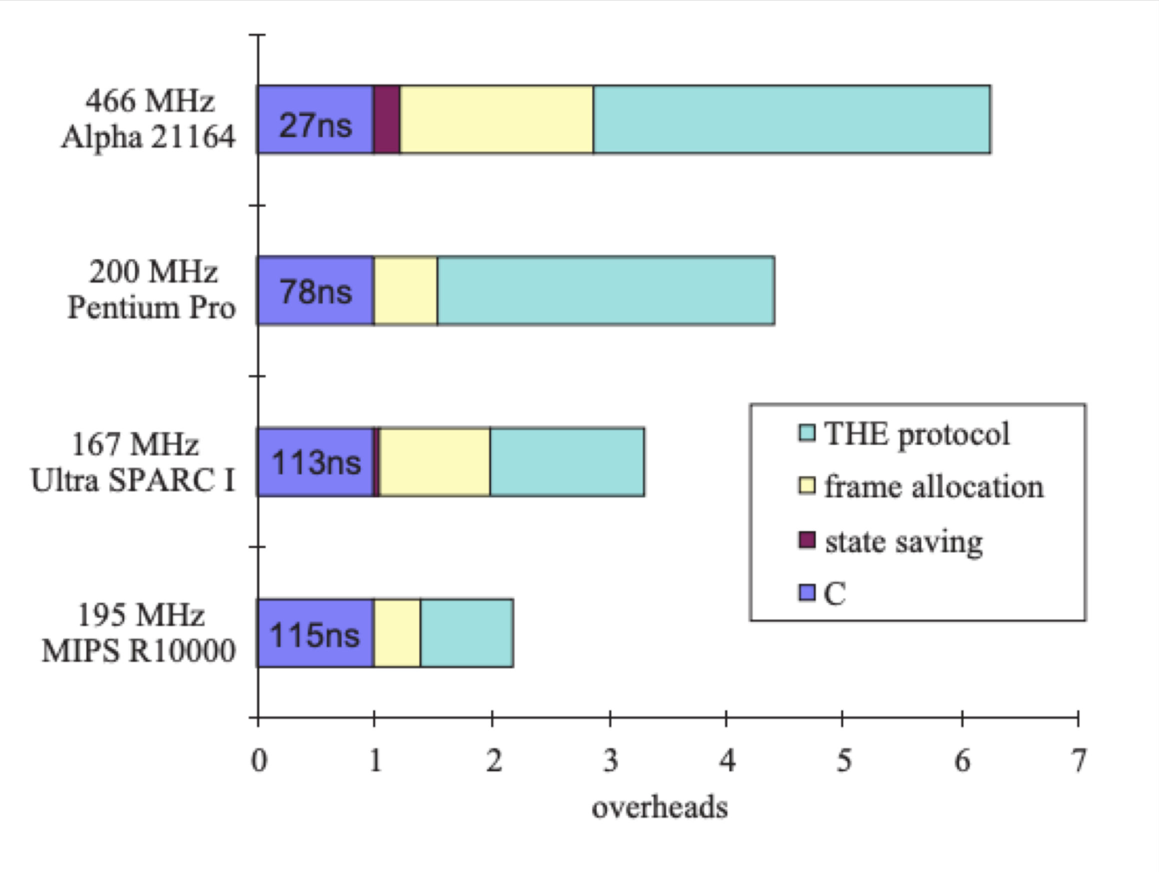
Thief

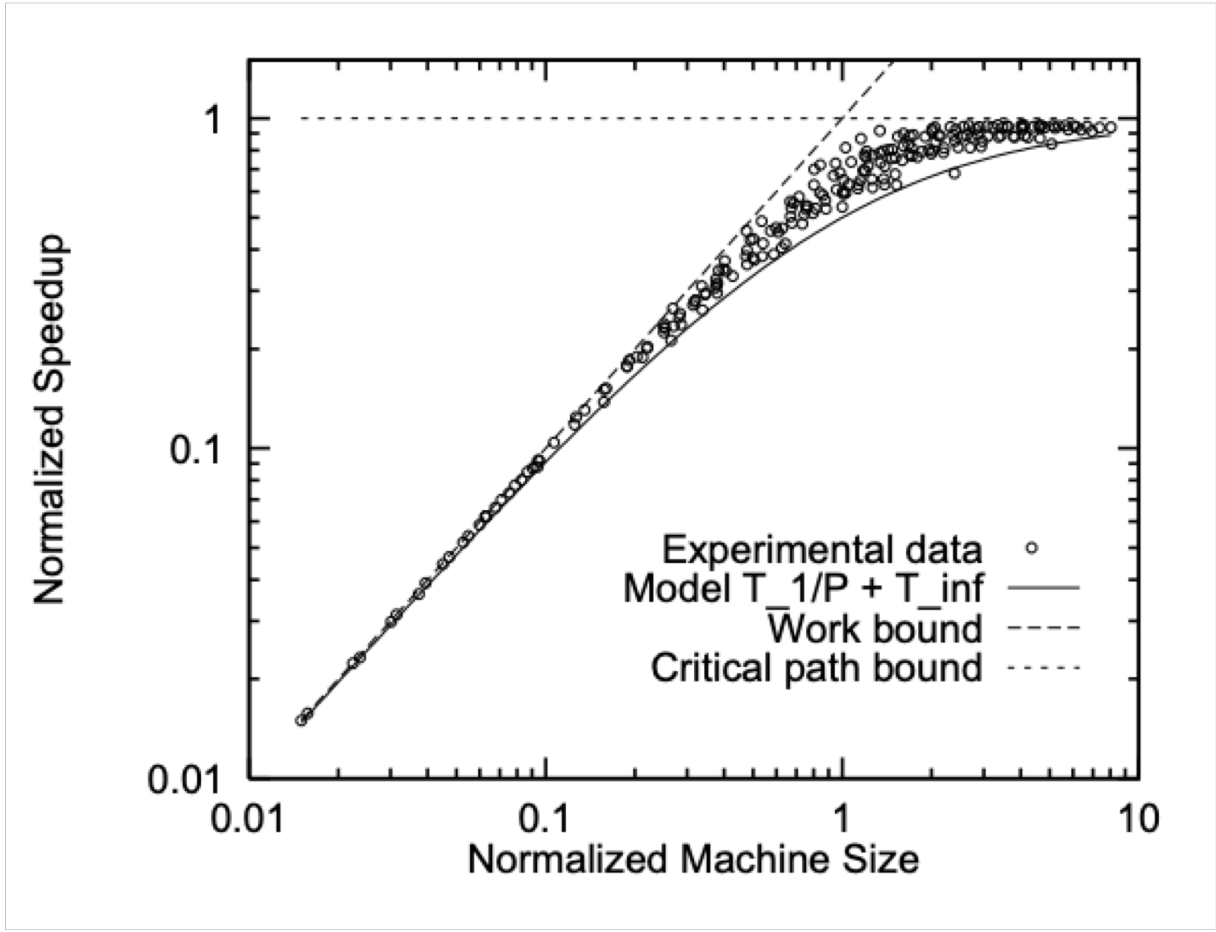
```
1   steal() {
2     lock(L);
3     H++;
4     if (H > T) {
5       H--;
6       unlock(L);
7       return FAILURE;
8     }
9     unlock(L);
10    return SUCCESS;
11  }
```

Benchmarks

Program	Size	T_1	T_∞	$\overline{P}$	c_1	T_8	T_1/T_8	T_S/T_8
fib	35	12.77	0.0005	25540	3.63	1.60	8.0	2.2
blockedmul	1024	29.9	0.0044	6730	1.05	4.3	7.0	6.6
notempmul	1024	29.7	0.015	1970	1.05	3.9	7.6	7.2
strassen	1024	20.2	0.58	35	1.01	3.54	5.7	5.6
*cilksort	4,100,000	5.4	0.0049	1108	1.21	0.90	6.0	5.0
†queens	22	150.	0.0015	96898	0.99	18.8	8.0	8.0
†knapsack	30	75.8	0.0014	54143	1.03	9.5	8.0	7.7
lu	2048	155.8	0.42	370	1.02	20.3	7.7	7.5
*cholesky	BCSSTK32	1427.	3.4	420	1.25	208.	6.9	5.5
heat	4096×512	62.3	0.16	384	1.08	9.4	6.6	6.1
fft	2^{20}	4.3	0.0020	2145	0.93	0.77	5.6	6.0
Barnes-Hut	2^{16}	124.	0.15	853	1.02	16.5	7.5	7.4

Benchmarks


466 MHz
Alpha 21164
27ns
200 MHz
Pentium Pro
78ns
167 MHz
Ultra SPARC I
113ns
195 MHz
MIPS R10000
115ns
THE protocol
frame allocation
state saving
C
0
1
2
3
4
5
6
7
overheads


Normalized Speedup
1
0.1
0.01
0.01
0.1
1
10
Normalized Machine Size
Experimental data
Model T_1/P + T_inf
Work bound
Critical path bound

Cilk++ Hyperobjects

- Non-local variables introduce "race conditions" in otherwise independent threads of multi-threaded program.
- A determinacy race exists if strands access the same shared location and at least one of the strands modifies values in the location.
- Code shows an example of walking down a binary tree to check for node property.
- There might be trouble in output_list!

```
bool has_property(Node *);
std::list<Node *> output_list;
// ...
void walk(Node *x)
{
  if (x) {
    if (has_property(x))
      output_list.push_back(x);
    walk(x->left);
    walk(x->right);
  }
}
```

```
bool has_property(Node *);
std::list<Node *> output_list;
// ...
void walk(Node *x)
{
  if (x) {
    if (has_property(x))
      output_list.push_back(x);
    cilk_spawn walk(x->left);
    walk(x->right);
    cilk_sync;
  }
}
```

Cilk++ Hyperobjects

- Solution: Associate a mutual-exclusion lock (mutex) L with output list.
- Mutex is acquired in line 9 and released in line 11.
- But, Mutex creates a bottleneck.
- Alternative may be to restructure the code to accumulate the output lists in each sub-computation. Ordering might be a challenge but may be possible.
- Hyperobjects – Linguistic construct that allows strands to coordinate in updating a shared variable.

```
1  bool has_property(Node *);
2  std::list<Node *> output_list;
3  mutex L;
4  // ...
5  void walk(Node *x)
6  {
7    if (x) {
8      if (has_property(x)) {
9        L.lock();
10       output_list.push_back(x);
11       L.unlock();
12     }
13     cilk_spawn walk(x->left);
14     walk(x->right);
15     cilk_sync;
16   }
17 }
```

More on Hyperobjects

- Hyperobject as seen by a given strand of execution is called a “view”
- Strands view is private, but when two or more strands combine their views are combined.
- Any query or update to the hyperobject may update the strand’s view.
- Why are hyperobjects important?
  - Simplify the parallelization of programs with non-local variable, without forcing the programmer to restructure logic of the program.

Cilk++ Reducers

- Similar Reduce?
  - Open MP – reduction clause
  - Intel Thread Building Blocks
  - Microsoft parallel Pattern Library – combinable object

- Result is declared as the reduction variable.
- Iterations of the loop spread across processors and local copies of the variable result are made.
- In order for the result to be same as serial code reduction operation- associative and commutative

```
int compute(const X& v);
int main()
{
  const std::size_t n = 1000000;
  extern X myArray[n];
  // ...
  int result(0);
  #pragma omp parallel for \
          reduction (+:result)
  for (std::size_t i = 0; i < n; ++i) {
    result += compute(myArray[i]);
  }
  std::cout << "The result is: " << result
            << std::endl;
  return 0;
}
```

Reducers in OpenMP

Cilk++ Reducers

- Reducers in Cilk++ similar to other languages with some augmentations
  - Can parallelize global or non-local variables
  - Associativity is necessary and sufficient.
  - Operate independently of control constructs
- Sum_reducer<int> declares result to be a reducer hyperobject over integers.
- Cilk for – all iterations of the loop can operate in parallel. This is similar to OpenMP but Cilk++ doesn't wait to combine local views

```
int compute(const X& v);
int cilk_main()
{
  const std::size_t n = 1000000;
  extern X myArray[n];
  // ...
  sum_reducer<int> result(0);
  cilk_for (std::size_t i = 0; i < n; ++i)
    result += compute(myArray[i]);

  std::cout << "The result is: "
            << result.get_value()
            << std::endl;
  return 0;
}
```

Cilk++ Reducers

- Tree walking code with reducers:
  - Declare a reducer output_list.
  - Output list has a list_append reducer operation
- Cilk++ runtime load balances computation.
- When the branches synchronize, the private views are reduced by concatenating the lists.
- No additional logic needs to be restructured!
- OpenMP, TBB and PPL have limitations w.r.t race-free parallelization.

```
bool has_property(Node *);
list_append_reducer<Node *> output_list;
// ...
void walk(Node *x)
{
  if (x) {
    if (has_property(x))
      output_list.push_back(x);
    cilk_spawn walk(x->left);
    walk(x->right);
    cilk_sync;
  }
}
```

Defining Reducers

```
struct sum_monoid : cilk::monoid_base<int> {
  void reduce(int* left, int* right) const {
    *left += *right;
  }
  void identity(int* p) const {
    new (p) int(0);
  }
};

cilk::reducer<sum_monoid> x;
```

- Define Reducers as Monoids:
  - Set *T*, operator *op* and identity *e*
  - Closure, identity and associative defined
- In Cilk++, class M inherits from cilk::monoid_base<T>.
- Class M supplies a reduce() and identity().
- View( ) -> runtime returns the local view as a reference to underlying type T upon which M is defined.
- Two disadvantages:
  - clumsy syntax: for incrementing x will be x.view()++
  - Access to reducer is unconstrained x.view() *=2
- Wrap reducers into abstract data types

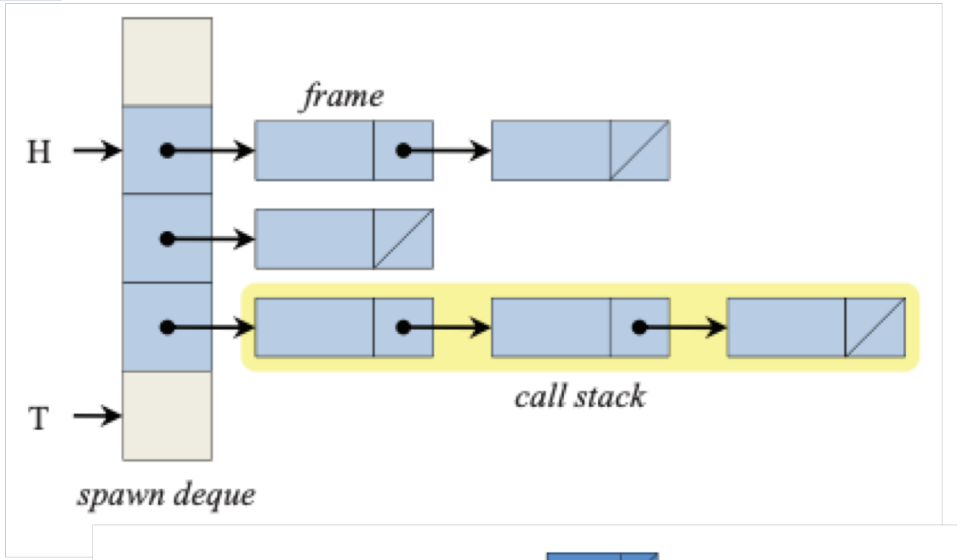
```
template<class T>
class sum_reducer
{
  struct Monoid : cilk::monoid_base<T> {
    void reduce(T* left, T* right) const {
      *left += *right;
    }
    void identity(T* p) const {
      new (p) T(0);
    }
  };

  cilk::reducer<Monoid> reducerImp;

public:
  sum_reducer() : reducerImp() { }

  explicit sum_reducer(const T &init)
    : reducerImp(init) { }

  sum_reducer& operator+=(T x) {
    reducerImp.view() += x;
    return *this;
  }

  sum_reducer& operator-=(T x) {
    reducerImp.view() -= x;
    return *this;
  }

  sum_reducer& operator++() {
    ++reducerImp.view();
    return *this;
  }

  void operator++(int) {
    ++reducerImp.view();
  }

  sum_reducer& operator--() {
    --reducerImp.view();
    return *this;
  }

  void operator--(int) {
    --reducerImp.view();
  }

  T get_value() const {
    return reducerImp.view();
  }
};
```

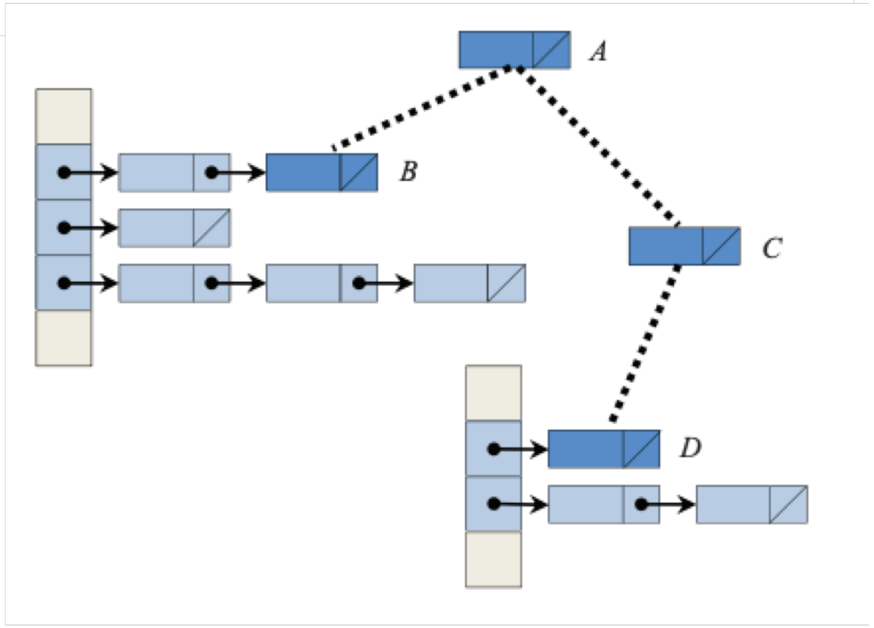
Semantics of Reducers

- View of the reducer is an object that is uniquely “owned” by one strand.
- Cilk_spawn and Cilk_sync execution transfers or creates additional views.
- Cilk_spawn creates two new cilk++ strands (child and continuation)
- X_C <- X_C op X_P ; Delete X_P ; Parent strand P becomes the new owner of X_C.
- Why not swap the view of cont and child?
  - Helps in serial execution and allows the entire program to executed with a single view with no overhead for reduce.
  - Parent having no view does not result in error because parent doesn’t resume till child has returned
- Cilk++ doesn’t wait for sync to reduce -> Need unbounded amount of memory to store all unreduced views.

Implementation of Reducers

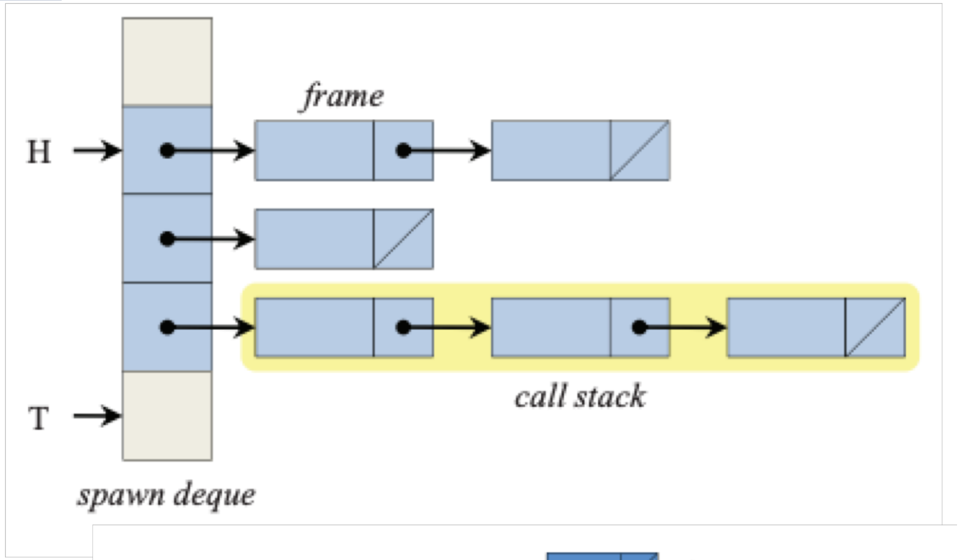
- Frames stalled at a cilk_sync lie outside any extended deque. The youngest frame of an extended deque has no children,. All other frames in the extended deque have exactly one child.
- Cilk++ partitions frames into two classes: stack frames, which only store a continuation and a parent pointer (but not a lock, join counter, or list of children), and full frames, which store the full parallel state

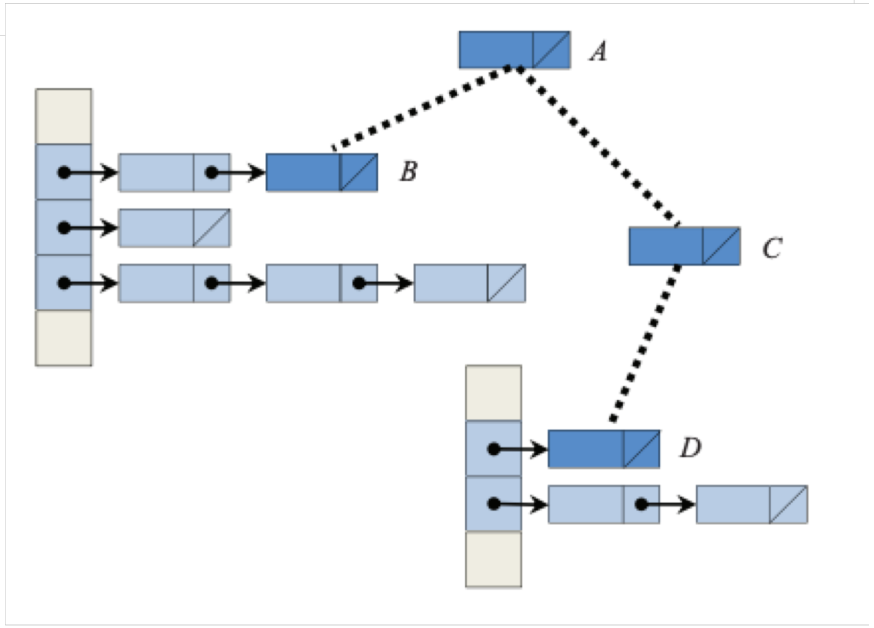




Implementation of Reducers

- Invariants:
  1. The oldest frame is a full frame
  2. A frame not belonging to deque is full frame
  3. All descendants of stack frames are stack frames
  4. Youngest frame on level-I stack is the parent of frame on level-i+1 stack
  5. A stack frame belongs to (only) one deque
  6. Oldest frame is a stack frame created by spawn or a full frame
  7. Every frame except the oldest frame was created by a function call.
  8. When a frame is stolen it is converted to a full frame
  9. A frame being executed is the youngest frame in deque
  10. Execution of stack frame (frame has no children) cilk_sync is a no op.

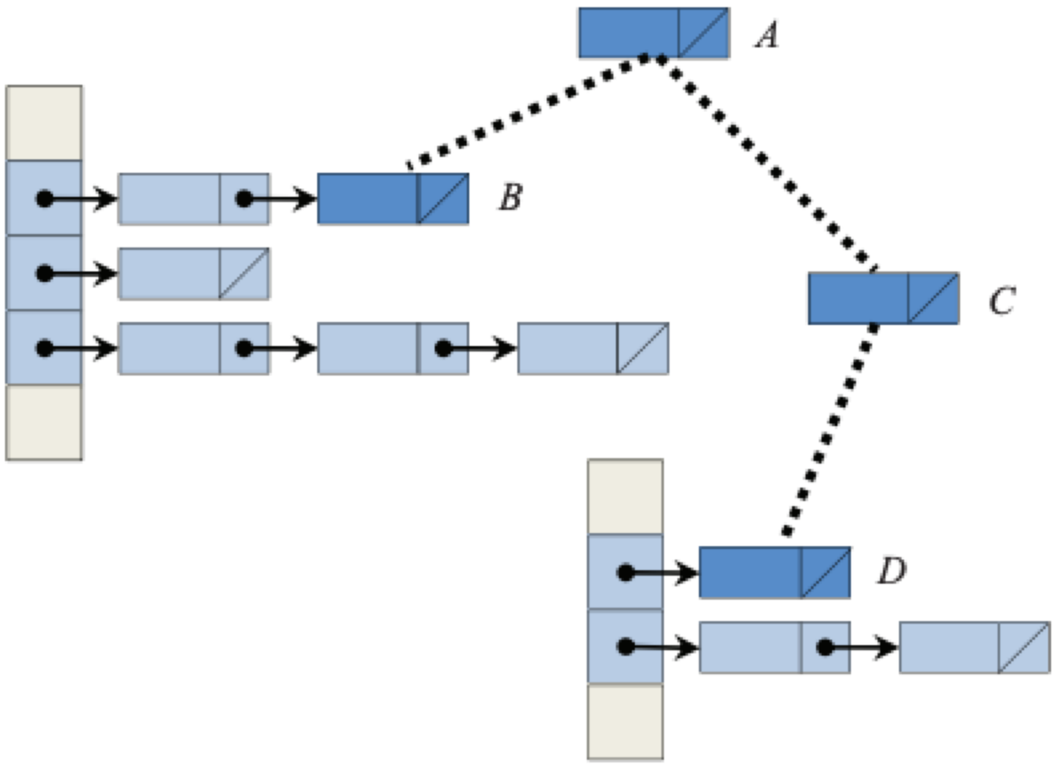




Implementation of Reducers

Function call. To call a procedure instance B from a procedure instance A, a worker sets the continuation in A's frame so that the execution of A resumes immediately after the call when B returns. The worker then allocates a stack frame for B and pushes B onto the current call stack as a child of A's frame. The worker then executes B.

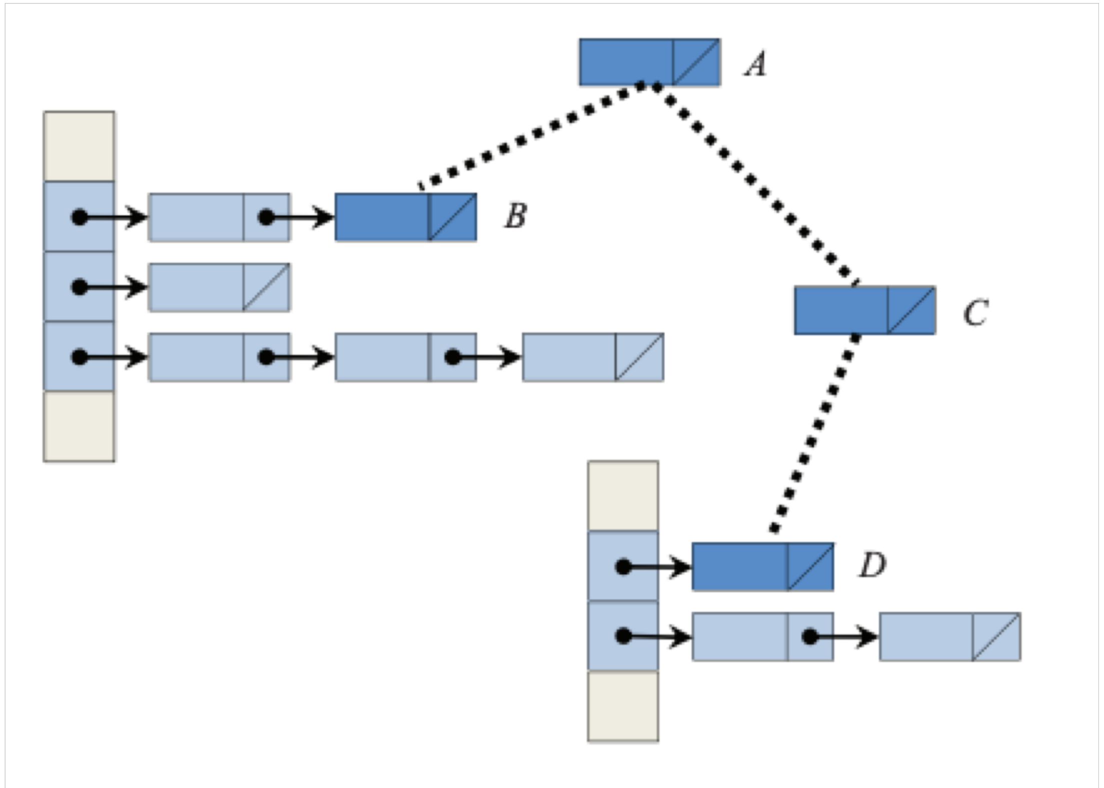
Spawn. To spawn a procedure instance B from a procedure instance A, a worker sets the continuation in A's frame so that the execution of A resumes immediately after the cilk_spawn statement. The worker then allocates a stack frame for B, pushes the current call stack onto the tail of its deque, and starts a fresh current call stack containing only B. The worker then executes B.



Implementation of Reducers

Return from a call. If the frame A executing the return is a stack frame, the worker pops A from the current call stack. The current call stack is now nonempty **(Invariant 6),** and its youngest frame is A'a parent.

Return from a spawn. If the frame A executing the return is a stack frame, the worker pops A from the current call stack, which empties it **(Invariant 7).** The worker tries to pop a call stack S from the tail of its deque. If the pop operation succeeds (the deque was nonempty), the execution continues from the continuation of A's parent (the youngest element of S), using S as the new current call stack. Otherwise, the worker begins random work stealing



Sync. If the frame A executing a cilk_sync is a stack frame, do nothing. (Invariant 10). Otherwise, A is a full frame with a join counter. Pop A from the current call stack (which empties the extended deque by Invariant 1), increment A's join counter, and steal A.

Modification for reducers

- Cilk++ uses address of reducer object as a key into hypermap hash table.
- Hypermap is lazy: elements are not stored until accessed for the first time
- Hypermaps maintained only in full frames
- USER hypermap, CHILDREN hypermap and RIGHT hypermap.

For left hypermap L and right hypermap R, we define the operation REDUCE(L,R) as follows. For all reducers $\mathbf{x}$, set

$$L(\mathbf{x}) \leftarrow L(\mathbf{x}) \otimes R(\mathbf{x}) ,$$

where $L(\mathbf{x})$ denotes the view resulting from the look-up of the address of $\mathbf{x}$ in hypermap L, and similarly for $R(\mathbf{x})$. The left/right distinction is important, because the operation $\otimes$ might not be commutative. If the operation $\otimes$ is associative, the result of the computation is the same as if the program executed serially. REDUCE is destructive: it updates L and destroys R, freeing all memory associated with R.

Modification for reducers

- **Return from a call**. Let C be a child frame of the parent frame P that originally called C, and suppose that C returns. We distinguish two cases: the “fast path” when C is a stack frame, and the “slow path” when C is a full frame.
  - If C is a stack frame, do nothing,
  - Otherwise, C is a full frame. We update $USER_P \leftarrow USER_C$, which transfers ownership of child views to the parent

- **Return from a spawn**. Let C be a child frame of the parent frame P that originally spawned C, and suppose that C returns.
  - If C is a stack frame, do nothing. Because C is a stack frame, P has not been stolen since C was spawned.
  - Otherwise, C is a full frame. We update USERC ← REDUCE(USERC, RIGHTC), which is to say that we reduce the views of all completed right-sibling frames of C into the views of C

Summary

- Cilk general purpose multithreading language based on C /C++ .
- Adopts Work-first principle based on the assumption of sufficient parallelism.
- Work-stealing protocol implemented on shared-memory between victim and thief processors.
- “THE” protocol results in significance performance speedup
- Efficient implementation of reducers and other hyperobjects help resolves determinacy race conditions.