Cilk Plus: Multicore extensions for C and C++

Matteo Frigo[1]

June 6, 2011

[1] Some slides courtesy of Prof. Charles E. Leiserson of MIT.

Intel® Cilk™ Plus

What is it?

C/C++ language extensions supporting fork/join and vector parallelism.

Features

- **Three simple keywords** for fork/join parallelism.
- **Cilkscreen**™ for accurate detection of determinacy races.
- **Cilkview**™ for analyzing parallelism.
- **Reducers** for resolving certain race conditions in a lock-free manner.
- Matlab™-style **array notation** for vector parallelism.
- Ships with the Intel® Parallel Building Blocks™.

Cilk language

Fibonacci

C++ elision

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

Cilk

```
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 is a **faithful** extension of C/C++. The **serial elision** of a Cilk program is a valid implementation.

Spawn and sync

Fibonacci

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cilk_spawn:

The child procedure may be executed in parallel with the parent.

`cilk_spawn` *grants permission* for parallel execution. It does not *command* parallel execution.

Spawn and sync

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cilk_spawn:

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cilk_sync:

Cannot be passed until all spawned children have returned.

Implicit `cilk_sync` at the end of every function.

Cactus stack

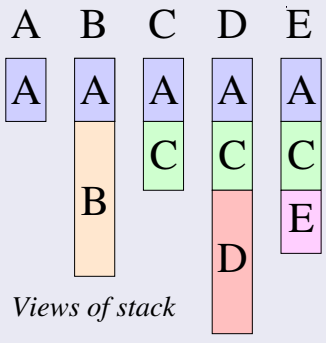
Cilk supports C's rule for pointers:

A pointer to stack space can be passed from parent to child, but not from child to parent. (Cilk also supports `malloc`.)

Cilk's cactus stack supports several stack views in parallel.

```
void A(void)
{
   cilk_spawn B();
   cilk_spawn C();
}

void C(void)
{
   cilk_spawn D();
   cilk_spawn E();
}
```



Parallel loops

Serial loop

```
for (int i = 0; i < n; ++i)
    foo(i);
```

Parallel loop

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

Serial loop that spawns

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

cilk_for:

Executes all iterations in parallel. Implicit `cilk_sync` waits for all spawned iterations. Iterates over integers and random-access iterators.

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cilk_sync;
```

cilk_for:

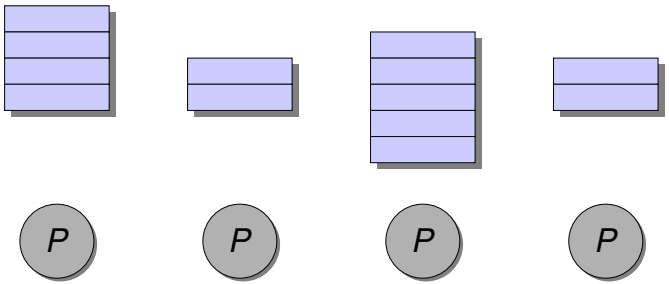
Executes all iterations in parallel. Implicit `cilk_sync` waits for all spawned iterations. Iterates over integers and random-access iterators.

Serial loop:

Long chain of dependencies: `++i` is serial.

The Cilk work-stealing scheduler

Each worker maintains a work deque, and it manipulates the bottom of the deque like a stack.



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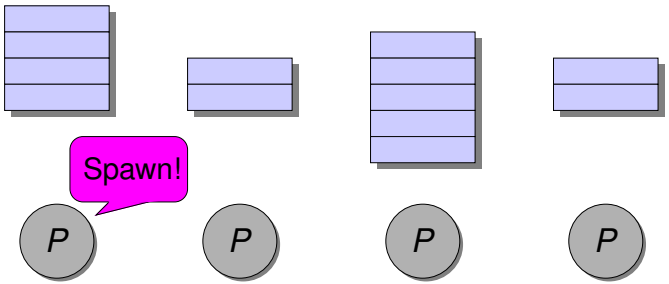

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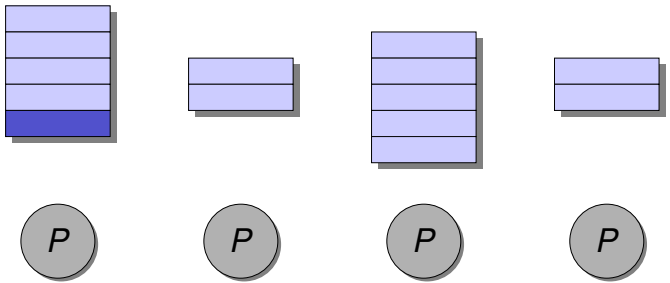

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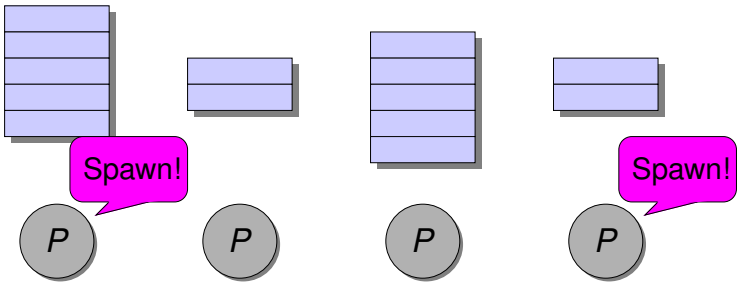

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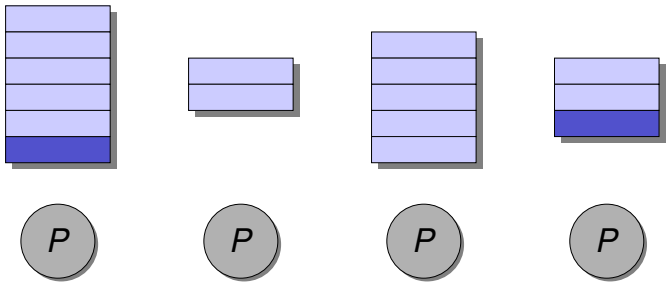

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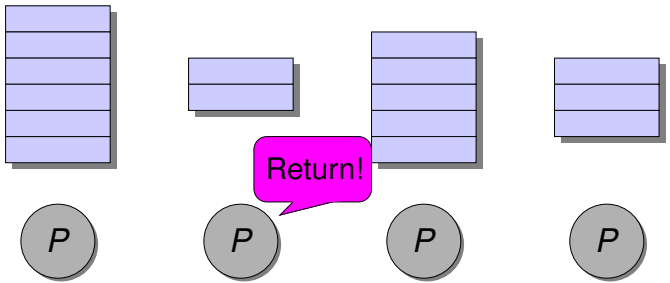

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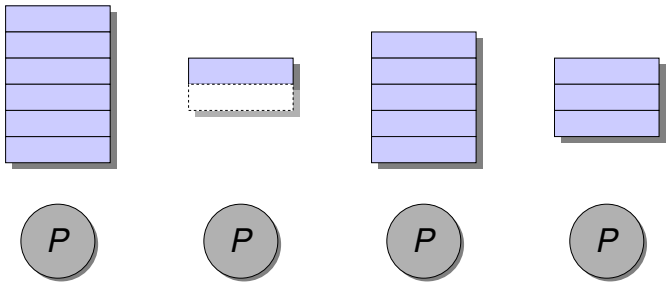

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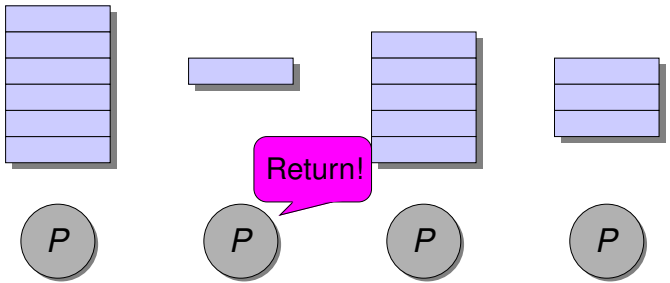

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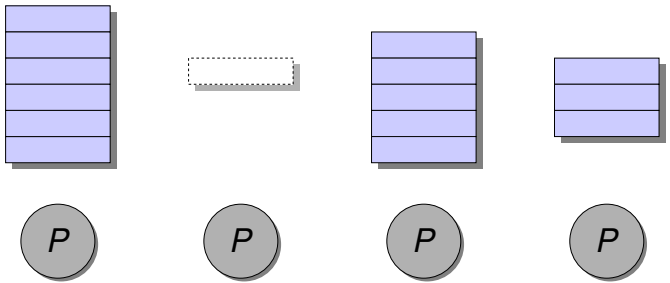

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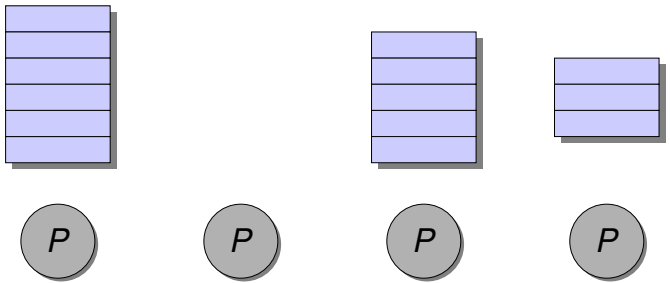

Randomized work stealing:

When a processor runs out of work, it steals a thread from the top of a random victim's deque.

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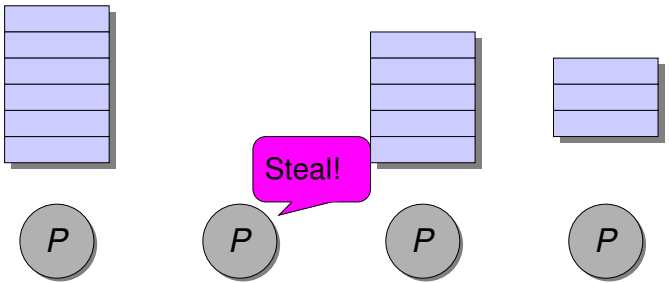

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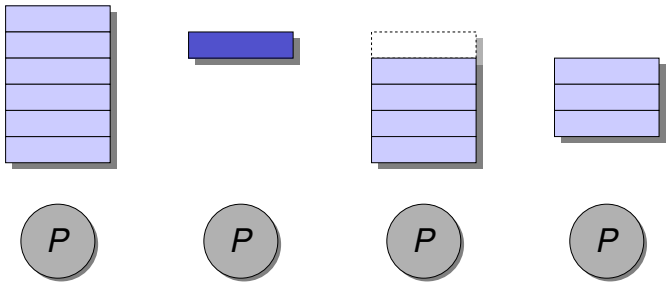

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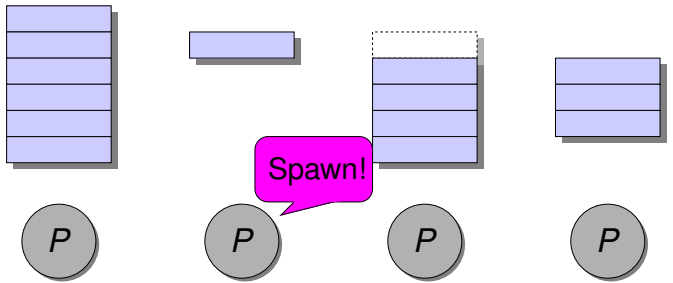

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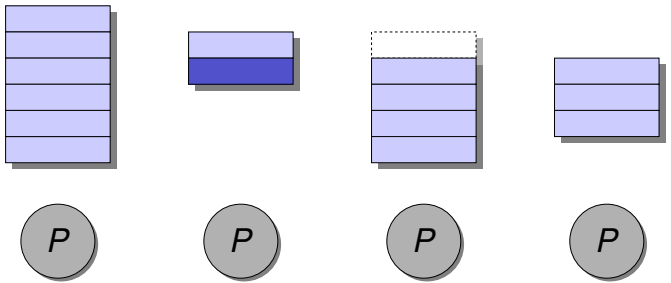

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The Cilkscreen race detector

Race bugs

Definition

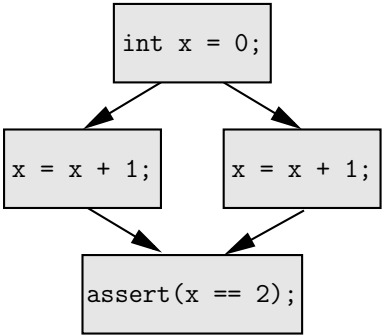
A **determinacy race** occurs when two logically parallel instructions access the same memory locations and at least one of the accesses is a write.

Example

```
int x = 0;

cilk_for (int i = 0; i < 2; ++i)
    x = x + 1;

assert(x == 2);
```



The Cilkscreen race detector

Correctness

Cilkscreen executes a program once on given input.

- If a race exists on a location, Cilkscreen reports a race on that location.
- No false positives: If a race does not exist, Cilkscreen reports no races.

Performance

- Constant memory overhead (about 4-5x), independent of the number of threads.
- (Almost) constant time overhead (about 10-50x), independent of the number of threads.

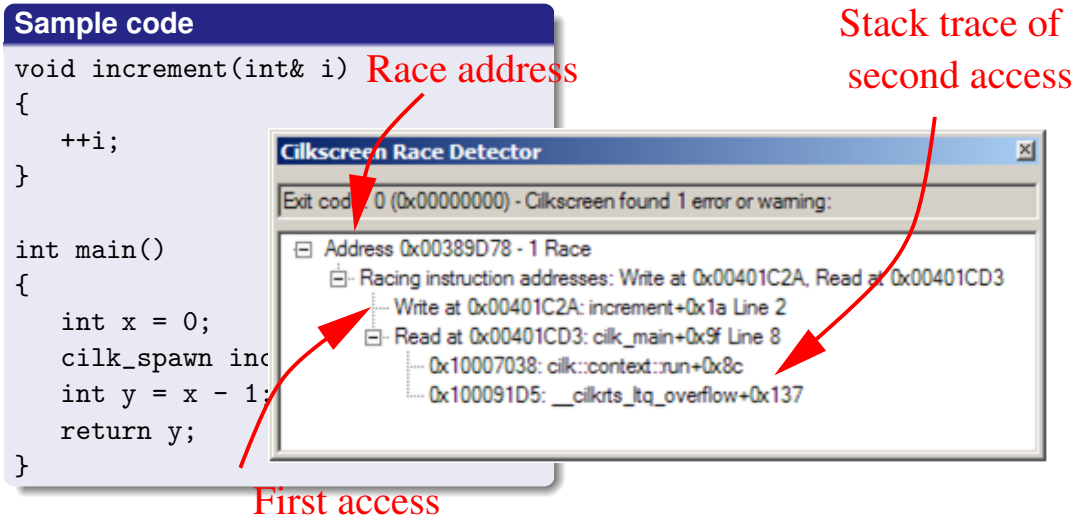
Cilkscreen screenshot

Sample code

```
void increment(int& i)
{
   ++i;
}

int main()
{
   int x = 0;
   cilk_spawn increment(x);
   int y = x - 1;
   return y;
}
```

Cilkscreen screenshot



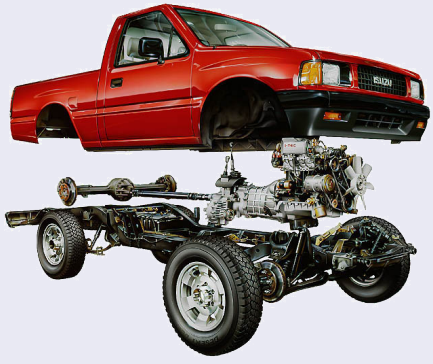
Cilkscreen in practice

- Executes production binaries. No separate “debug” binary is necessary.
- Identifies source locations and symbolic addresses involved in races.
- Reports the location of the first access and a stack trace of the second access.
- Is a debugger, not a symbolic theorem prover. It only analyzes paths that are actually executed.
- Understands locks.
- Supports various pragmas, e.g. for annotating intentional races.

Reducers

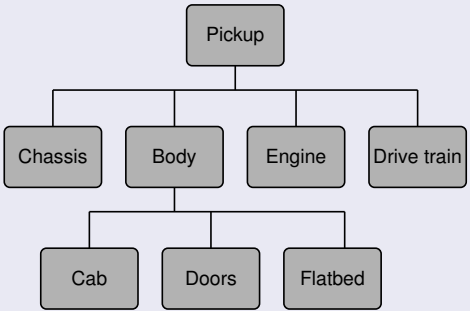
Collision detection

Mechanical assembly:



Internal representation:

Tree of subassemblies down to individual parts.



Problem:

Find all “collisions” between two assemblies.

Simplified collision detection

Goal:

Create a list of all the parts in a mechanical assembly that collide with a given target object.

Pseudo code:

```
Node *target;
std::list<Node *> output_list;

void walk(Node *x) {
  if (x->kind == Node::LEAF) {
    if (target->collides_with(x)) {
        output_list.push_back(x);
    }
  } else {
    for (Node::iterator child = x.begin();
         child != x.end();
         ++child) {
        walk(child);
    }
  }
}
```

Naive parallelization

Problem:

Race condition on the global variable `output_list`.

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}
```

Locking solution

Problems:

Lock contention inhibits speedup.

Output order is nondeterministic.

Pseudo code:

```
mutex lock;

void walk(Node *x) {
  if (x->kind == Node::LEAF) {
    if (target->collides_with(x)) {
        lock.acquire();
        output_list.push_back(x);
        lock.release();
    }
  } else {
    cilk_for (Node::iterator child = x.begin();
         child != x.end();
         ++child) {
        walk(child);
    }
  }
}
```

Reducers

Reducer solution:

- Define `output_list` as a **reducer**.
- No code restructuring.
- The output is in serial order.
- No locking.
- Low overhead.

Pseudo code:

```
Node *target;
cilk::reducer_list_append<Node *> output_list;

void walk(Node *x) {
  if (x->kind == Node::LEAF) {
    if (target->collides_with(x)) {
        output_list.push_back(x);
    }
  } else {
    cilk_for (
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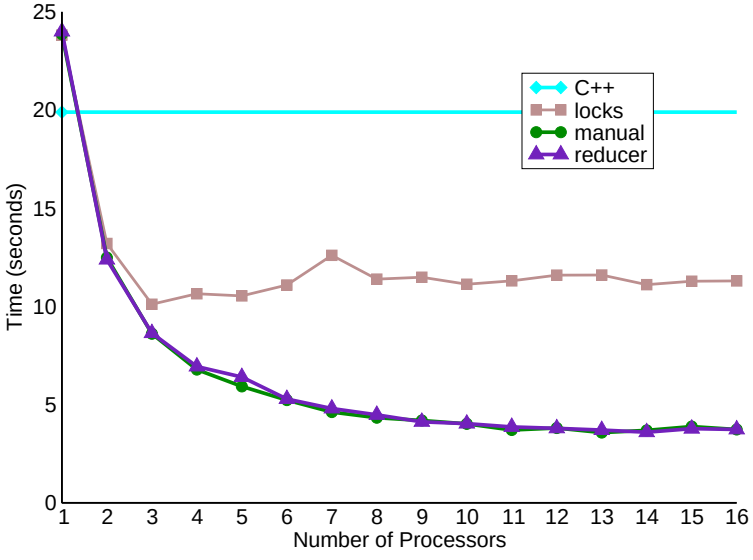
Performance of collision detection



Reducers

Properties:

- “Hyperobjects” that support multiple parallel “views”.
- Automatic, user-defined, pairwise merging of views following the fork/join structure of the program.
- Deterministic if the merge operation is associative.
- Multiple reductions can execute in parallel.
- Backward-compatible with sequential semantics (and syntax).

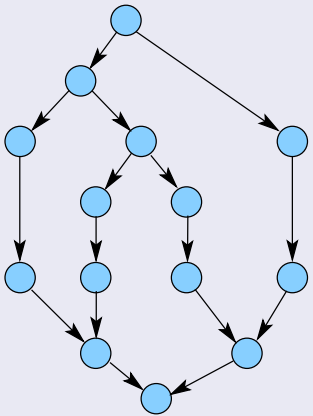
Applications:

- Mapreduce pattern (such as collision detection).
- C++ exceptions.
- Volpack volume rendering.
- File output in bzip2.

The Cilkview parallelism analyzer

What is parallelism?

Dependency graph



Measures:

- T_P = execution time on P processors

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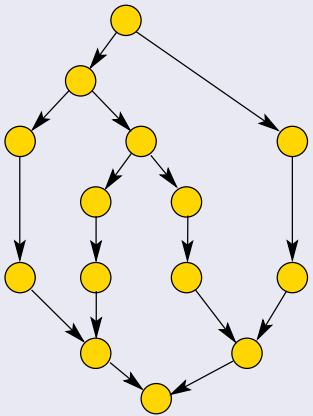

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- T_1 = **work**

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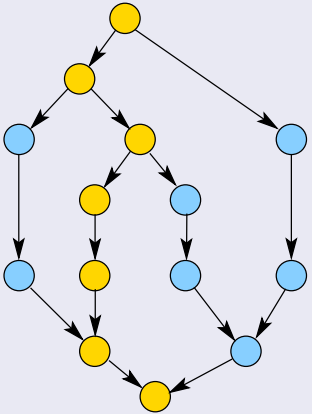

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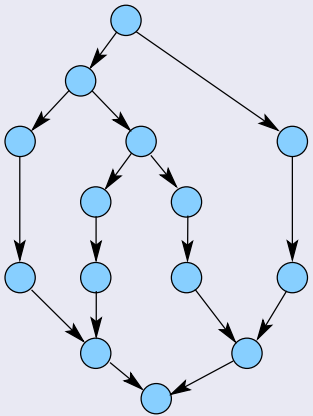

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Work Law:

$$T_P \geq T_1/P.$$

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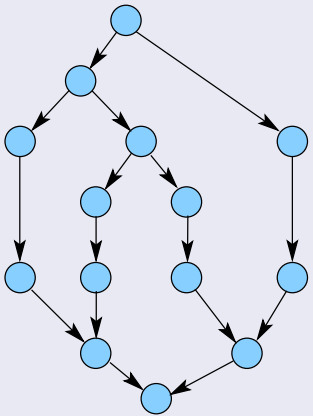

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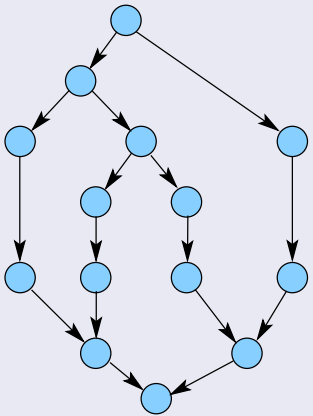

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Span Law:

$$T_P \geq T_\infty.$$

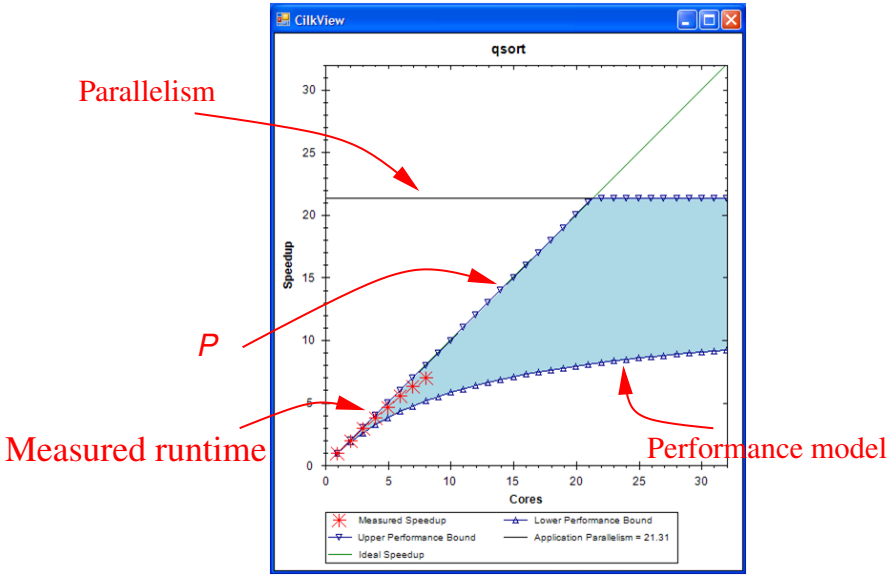
Maximum speedup:

$$\text{speedup} = T_1/T_P \leq T_1/T_\infty = \textbf{parallelism}.$$

The Cilkview parallelism analyzer

- Computes work and span of Cilk programs.
- Instruments production binaries. No debug version required.
- Counts instructions, not time.
- Produces textual and/or graphical output.
- Can measure work and span of portions of a program.
- Fast (about 5x slowdown).
- Negligible memory overhead.

Cilkview screenshot



Where does the performance model come from?

Theorem

Theorem: Cilk's work-stealing scheduler achieves an expected running time of

$$T_P = T_1/P + O(T_\infty)$$

on P processors.

Pseudoproof (not quite correct).

A processor is either working or stealing. The total time all processors spend working is T_1. Each steal has a $1/P$ chance of reducing the span by 1. Thus, the expected number of steals is $O(PT_\infty)$. Since there are P processors, the expected time is

$$(T_1 + O(PT_\infty))/P = T_1/P + O(T_\infty) \ .$$

□

Intel Parallel Building Blocks

- Suite of compilers, libraries and tools for parallelism.
- Cilk keywords for C and C++.
- Cilkscreen, Cilkview.
- Automatic vectorization for SSE/SSE2/AVX/etc.
- Data-parallel array notation: `a[0:n] = b[0:n] + 1`.
- Threading Building Blocks.
- Supports Linux™ and Windows®.

History of Cilk

1992: Theory of the Cilk scheduler. [Blumofe and Leiserson]
1993: Early Cilk implementations on CM-5.
1995: Modern Cilk language. [Blumofe et al.]
1998: Modern Cilk implementation. [Frigo et al.]
1998: Race detector. [Feng and Leiserson]
2004: Adaptive scheduling. [Agrawal]
2005: Exceptions, JCilk. [Danaher et al.]
2007: Cilk Arts founded. [Frigo and Leiserson]
2007: Cilk++ language and implementation.
2009: Cilk Arts acquired by Intel.
2010: Cilk Plus: array notation, integration with Intel tools.

Conclusion

- The Cilk language is a simple expression of fork-join parallelism.
- Cilkscreen detects determinacy races.
- Reducers cure a common set of races.
- Cilkview analyzes the parallelism of your program.
- Cilk Plus is integrated with data-parallel extensions, SIMD instructions, and TBB.
- Emphasis on compatibility with sequential software.

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