Multicore programming in CilkPlus

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From Cilk to Cilk++ and Cilk Plus

- `Cilk` has been developed since 1994 at the MIT Laboratory for Computer Science by Prof. Charles E. Leiserson and his group, in particular by Matteo Frigo.
- Besides being used for research and teaching, `Cilk` was the system used to code the three world-class chess programs: Tech, Socrates, and Cilkchess.
- Over the years, the implementations of `Cilk` have run on computers ranging from networks of Linux laptops to an 1824-nodes Intel Paragon.
- From 2007 to 2009 Cilk has lead to `Cilk++`, developed by Cilk Arts, an MIT spin-off, which was acquired by Intel in July 2009 and became CilkPlus, see `http://www.cilk.com/`
- `CilkPlus` can be freely downloaded for Linux as a branch of the `gcc` compiler collection.
- `Cilk` is still developed at MIT `http://supertech.csail.mit.edu/cilk/`

Cilk++ (and Cilk Plus)

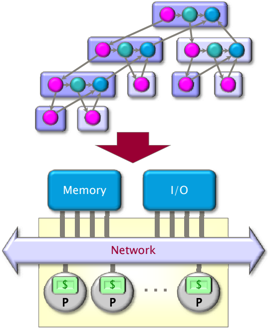
- CilkPlus (resp. Cilk) is a small set of linguistic extensions to C++ (resp. C) supporting fork-join parallelism
- Both Cilk and CilkPlus feature a provably efficient work-stealing scheduler.
- CilkPlus provides a hyperobject library for parallelizing code with global variables and performing reduction for data aggregation.
- CilkPlus includes the Cilkscreen race detector and the Cilkview performance analyzer.

Fork-Join Parallelism in CilkPlus

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

- The named child function `cilk_spawn fib(n-1)` may execute in parallel with its parent
- `CilkPlus` keywords `cilk_spawn` and `cilk_sync` grant permissions for parallel execution. They do not command parallel execution.

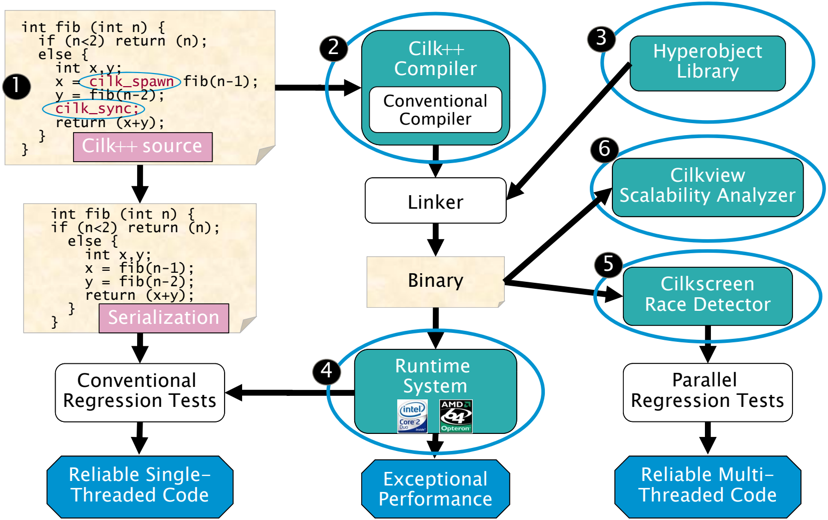
Scheduling



A **scheduler**'s job is to map a computation to particular processors. Such a mapping is called a **schedule**.

- If decisions are made at runtime, the scheduler is *online*, otherwise, it is *offline*
- `CilkPlus`'s scheduler maps strands onto processors dynamically at runtime.

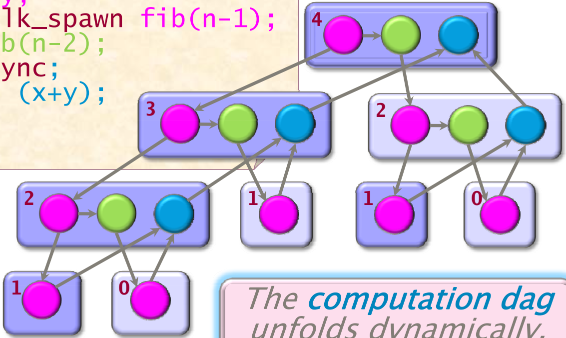
The CilkPlus Platform



The fork-join parallelism model

```
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);
  }
}
```

Example:
`fib(4)`



"Processor oblivious"

*The **computation dag** unfolds dynamically.*

We shall also call this model **multithreaded parallelism**.

The fork-join parallelism model

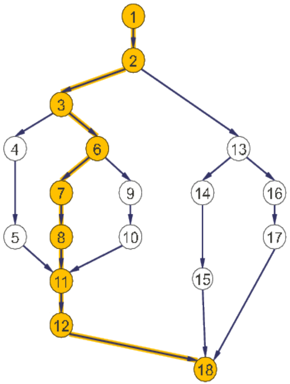
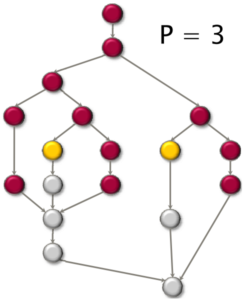


Figure: Instruction stream DAG.

- T_p is the minimum running time on p processors.
- T_1 is the sum of the number of instructions at each vertex in the DAG, called the **work**.
- T_∞ is the minimum running time with infinitely many processors, called the **span**. This is the length of a path of maximum length from the root to a leaf.
- T_1/T_∞ : **Parallelism**.
  - *Work law:* $T_p \geq T_1/p$.
  - *Span law:* $T_p \geq T_\infty$.

Graham - Brent Theorem



- In any *greedy schedule*, there are two types of steps:
  - **complete step**: There are at least p strands that are ready to run. The greedy scheduler selects any p of them and runs them.
  - **incomplete step**: There are strictly less than p threads that are ready to run. The greedy scheduler runs them all.
- *For any greedy schedule, we have* $T_p \;\leq\; T_1/p \;+\; T_\infty$

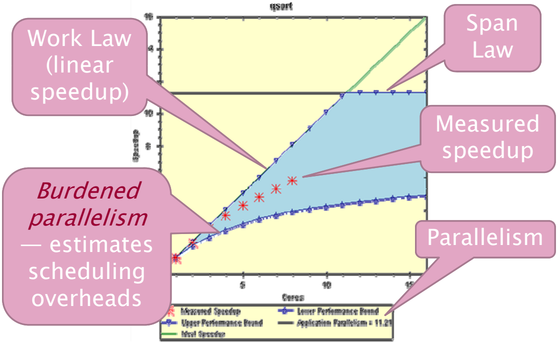
Speedup on p processors

- T_1/T_p is called the **speedup on p processors**
- A parallel program execution can have:
  - **linear speedup**: $T_1/T_P = \Theta(p)$
  - **superlinear speedup**: $T_1/T_P = \omega(p)$ (not possible in this model, though it is possible in others)
  - **sublinear speedup**: $T_1/T_P = o(p)$

Overheads and burden

- Many factors (simplification assumptions of the fork-join parallelism model, architecture limitation, costs of executing the parallel constructs, overheads of scheduling) will make T_p larger in practice than $T_1/p + T_\infty$.
- One may want to estimate the impact of those factors:
  1. by improving the estimate of the *randomized work-stealing complexity result*
  2. by comparing a `CilkPlus` program with its `C++` elision
  3. by estimating the costs of spawning and synchronizing
- `CilkPlus` estimates T_p as $T_p = T_1/p + 1.7\ \mathrm{burden\_span}$, where $\mathrm{burden\_span}$ is 15000 instructions times the number of continuation edges along the critical path.

Cilkview



- `Cilkview` computes work and span to derive upper bounds on parallel performance
- `Cilkview` also estimates scheduling overhead to compute a burdened span for lower bounds.

The cilkview example from the documentation

Using cilk_for to perform operations over an array in parallel:

```
static const int COUNT = 4;
static const int ITERATION = 1000000;
long arr[COUNT];
long do_work(long k){
  long x = 15;
  static const int nn = 87;
  for (long i = 1; i < nn; ++i)
    x = x / i + k % i;
  return x;
}
int main(){
  for (int j = 0; j < ITERATION; j++)
    cilk_for (int i = 0; i < COUNT; i++)
      arr[i] += do_work( j * i + i + j);
}
```

```
1) Parallelism Profile
   Work :                                 6,480,801,250 ins
   Span :                                 2,116,801,250 ins
   Burdened span :                        31,920,801,250 ins
   Parallelism :                                  3.06
   Burdened parallelism :                         0.20
   Number of spawns/syncs:                        3,000,000
   Average instructions / strand :                720
   Strands along span :                           4,000,001
   Average instructions / strand on span : 529
2) Speedup Estimate
   2 processors:          0.21 - 2.00
   4 processors:          0.15 - 3.06
   8 processors:          0.13 - 3.06
   16 processors:         0.13 - 3.06
   32 processors:         0.12 - 3.06
```

A simple fix

Inverting the two for loops

```
int main()
{
  cilk_for (int i = 0; i < COUNT; i++)
    for (int j = 0; j < ITERATION; j++)
      arr[i] += do_work( j * i + i + j);
}
```

```
1) Parallelism Profile
   Work :                                  5,295,801,529 ins
   Span :                                  1,326,801,107 ins
   Burdened span :                         1,326,830,911 ins
   Parallelism :                                  3.99
   Burdened parallelism :                         3.99
   Number of spawns/syncs:                        3
   Average instructions / strand :                529,580,152
   Strands along span :                           5
   Average instructions / strand on span: 265,360,221
2) Speedup Estimate
   2 processors:           1.40 - 2.00
   4 processors:           1.76 - 3.99
   8 processors:           2.01 - 3.99
   16 processors:          2.17 - 3.99
   32 processors:          2.25 - 3.99
```

Timing

	#cores = 1	#cores = 2		#cores = 4	
version	timing(s)	timing(s)	speedup	timing(s)	speedup
original	7.719	9.611	0.803	10.758	0.718
improved	7.471	3.724	2.006	1.888	3.957