Issues in Parallelization

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Cilk Arts

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Outline

Goal: highlight common performance problems in parallel programs.

- Wrong grain size in `cilk_for` loops.
- Too little parallelism.
- Memory bandwidth limitations.
- Too little burdened parallelism.

How:

- Run microbenchmarks.
- Explain why they do or do not work as intended.

Example 1: a small loop with grain size = 1

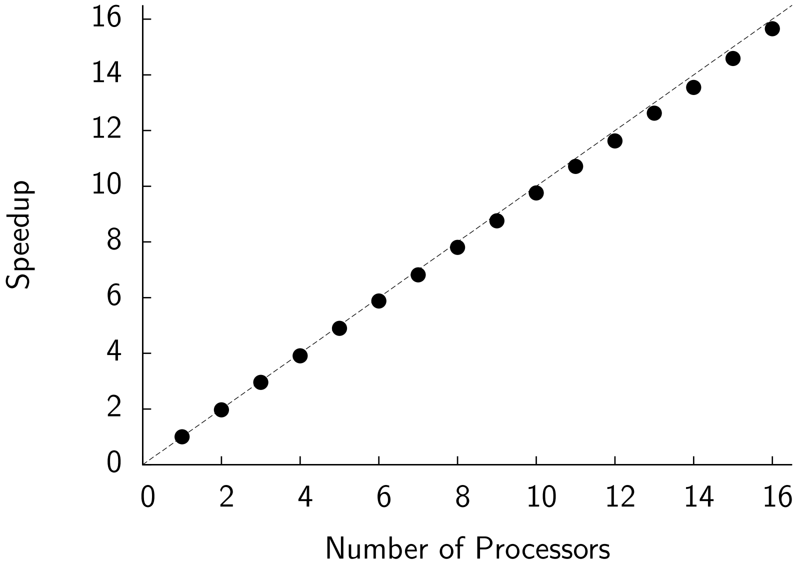
Code:

```
const int N = 100 * 1000 * 1000;

void cilk_for_grainsize_1()
{
#pragma cilk_grainsize = 1
    cilk_for (int i = 0; i < N; ++i)
        fib(2);
}
```

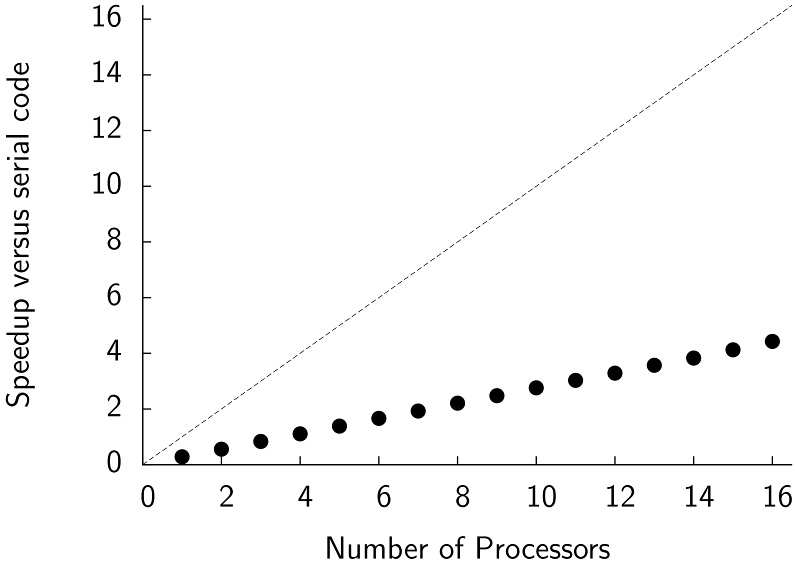
Expectations:

- Parallelism should be large, perhaps $\Theta(N)$ or $\Theta(N/\log N)$.
- We should see great speedup.

Speedup is indeed great. . .



... but performance is lousy



How `cilk_for` is implemented

Source:

```
cilk_for (int i = A; i < B; ++i)
     BODY(i)
```

Implementation:

```
void recur(int lo, int hi) {
     if ((hi - lo) > GRAINSIZE) {
          int mid = lo + (hi - lo) / 2;
          cilk_spawn recur(lo, mid);
          cilk_spawn recur(mid, hi);
     } else
          for (int i = lo; i < hi; ++i)
               BODY(i);
}

recur(A, B);
```

Default grain size

Cilk++ chooses a grain size if you don't specify one.

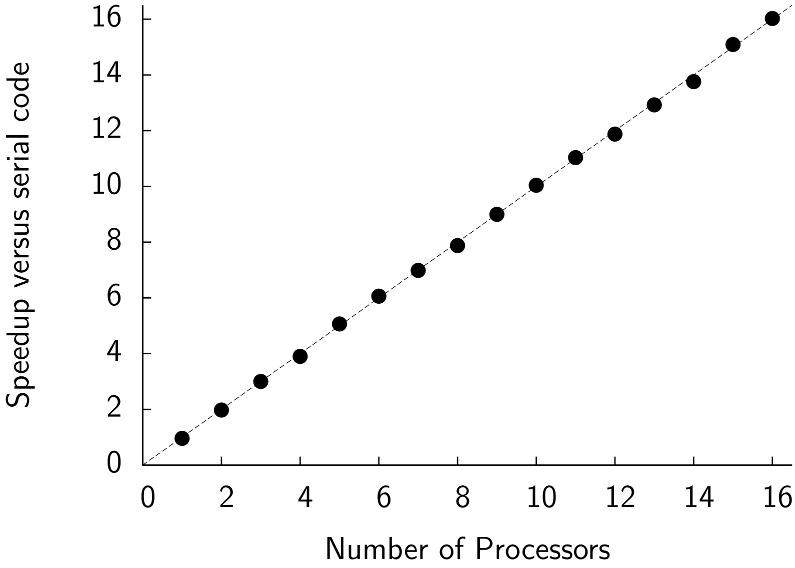
```
void cilk_for_default_grainsize()
{
    cilk_for (int i = 0; i < N; ++i)
        fib(2);
}
```

Cilk++'s heuristic for the grain size:

$$\text{grain size} = \min\left\{\frac{N}{8P}, 512\right\} .$$

- Generates about $8P$ parallel leaves.
- Works well if the loop iterations are not too unbalanced.

Speedup with default grain size



Large grain size

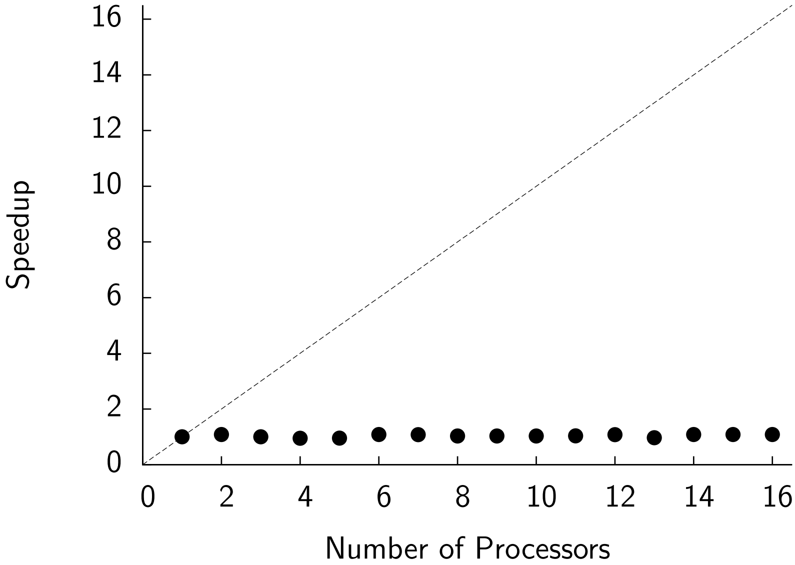
A large grain size should be even faster, right?

```
void cilk_for_large_grainsize()
{
#pragma cilk_grainsize = N
    cilk_for (int i = 0; i < N; ++i)
        fib(2);
}
```

Actually, no (except for noise):

Grain size	Runtime
1	8.55 s
default (= 512)	2.44 s
N (= 10^8)	2.42 s

Speedup with grain size = N



Tradeoff between grain size and parallelism

Use the PPA to understand the tradeoff:

Grain size	Parallelism
1	6,951,154
default (= 512)	248,784
N $(= 10^8)$	1

In the PPA, $P = 1$:

$$\text{default grain size} = \min\left\{\frac{N}{8P}, 512\right\} = \min\left\{\frac{N}{8}, 512\right\} .$$

Lessons learned

- Measure overhead before measuring speedup.
  - Compare 1-processor Cilk++ versus serial code.
- Small grain size $\Rightarrow$ higher work overhead.
- Large grain size $\Rightarrow$ less parallelism.
- The default grain size is designed for small loops that are reasonably balanced.
  - You may want to use a smaller grain size for unbalanced loops or loops with large bodies.
- Use the PPA to measure the parallelism of your program.

Example 2: A `for` loop that spawns

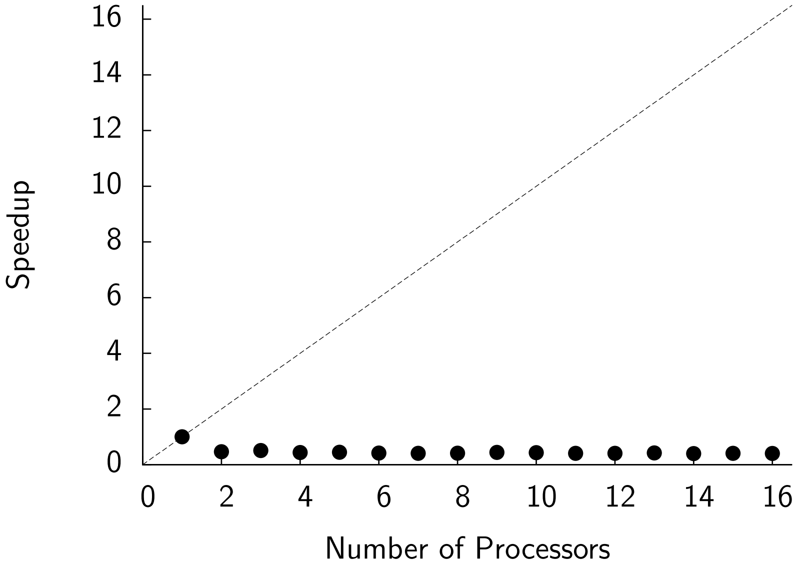
Code:

```
const int N = 10 * 1000 * 1000;

/* empty test function */
void f() { }

void for_spawn()
{
    for (int i = 0; i < N; ++i)
        cilk_spawn f();
}
```

Expectations:

- I am spawning N parallel things.
- Parallelism should be $\Theta(N)$, right?

“Speedup” of `for_spawn()`



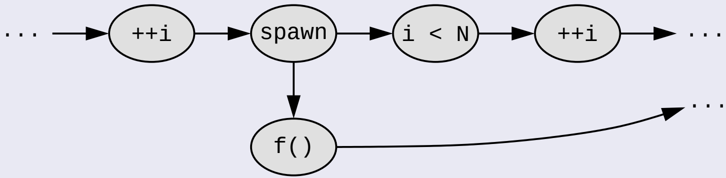
Insufficient parallelism

PPA analysis:

- PPA says that both work and span are $\Theta(N)$.
- Parallelism is ≈ 1.62, independent of N.
- Too little parallelism: no speedup.

Why is the span $\Theta(N)$?

```
for (int i = 0; i < N; ++i)
    cilk_spawn f();
```



Alternative: a `cilk_for` loop.

Code:

```
/* empty test function */
void f() { }

void test_cilk_for()
{
    cilk_for (int i = 0; i < N; ++i)
        f();
}
```

PPA analysis:

The parallelism is about 2000 (with default grain size).

- The parallelism is high.
- As we saw earlier, this kind of loop yields good performance and speedup.

Lessons learned

- `cilk_for()` is different from `for(...) cilk_spawn`.
- The span of `for(...) cilk_spawn` is $\Omega(N)$.
- For simple flat loops, `cilk_for()` is generally preferable because it has higher parallelism.
- (However, `for(...) cilk_spawn` might be better for recursively nested loops.)
- Use the PPA to measure the parallelism of your program.

Example 3: Vector addition

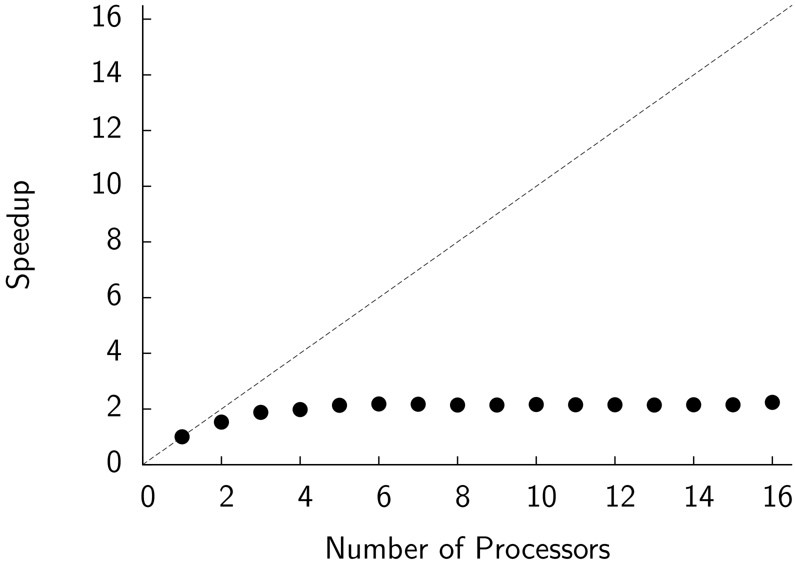
Code:

```
const int N = 50 * 1000 * 1000;

double A[N], B[N], C[N];

void vector_add()
{
    cilk_for (int i = 0; i < N; ++i)
        A[i] = B[i] + C[i];
}
```

Expectations:

- The PPA says that the parallelism is 68,377.
- This will work great!

Speedup of `vector_add()`



Bandwidth of the memory system

A typical machine: AMD Phenom 920 (Feb. 2009).

Cache level	daxpy bandwidth
L1	19.6 GB/s per core
L2	18.3 GB/s per core
L3	13.8 GB/s shared
DRAM	7.1 GB/s shared

daxpy: `x[i] = a*x[i] + y[i]`, double precision.

The memory bottleneck:

- A single core can generally saturate most of the memory hierarchy.
- Multiple cores that access memory will conflict and slow each other down.

How do you determine if memory is a bottleneck?

Hard problem:

- No general solution.
- Requires guesswork.

Two useful techniques:

- Use a profiler such as the Intel VTune.
  - Interpreting the output is nontrivial.
  - No sensitivity analysis.
- Perturb the environment to understand the effect of the CPU and memory speeds upon the program speed.

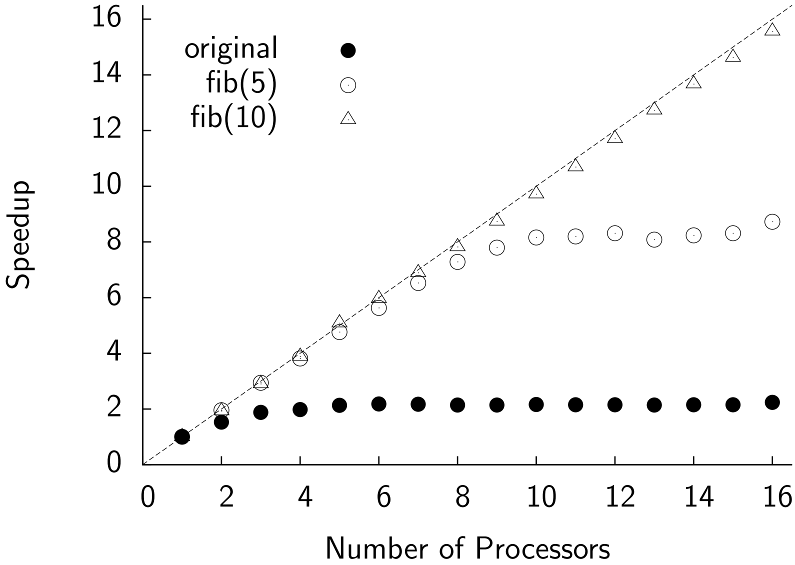
How to perturb the environment

- Overclock/underclock the processor, e.g. using the power controls.
  - If the program runs at the same speed on a slower processor, then the memory is (probably) a bottleneck.
- Overclock/underclock the DRAM from the BIOS.
  - If the program runs at the same speed on a slower DRAM, then the memory is not a bottleneck.
- Add spurious work to your program while keeping the memory accesses constant.
- Run P independent copies of the serial program concurrently.
  - If they slow each other down then memory is probably a bottleneck.

Perturbing vector_add()

```
const int N = 50 * 1000 * 1000;

double A[N], B[N], C[N];

void vector_add()
{
    cilk_for (int i = 0; i < N; ++i) {
        A[i] = B[i] + C[i];
        fib(5);  // waste time
    }
}
```

Speedup of perturbed `vector_add()`



Interpreting the perturbed results

The memory is a bottleneck:

- A little extra work (`fib(5)`) keeps 8 cores busy. A little more extra work (`fib(10)`) keeps 16 cores busy.
- Thus, we have enough parallelism.
- The memory is *probably* a bottleneck. (If the machine had a shared FPU, the FPU could also be a bottleneck.)

OK, but how do you fix it?

- `vector_add` cannot be fixed in isolation.
- You must generally restructure your program to increase the reuse of cached data. Compare the iterative and recursive matrix multiplication from yesterday.
- (Or you can buy a newer CPU and faster memory.)

Lessons learned

- Memory is a common bottleneck.
- One way to diagnose bottlenecks is to perturb the program or the environment.
- Fixing memory bottlenecks usually requires algorithmic changes.

Example 4: Nested loops

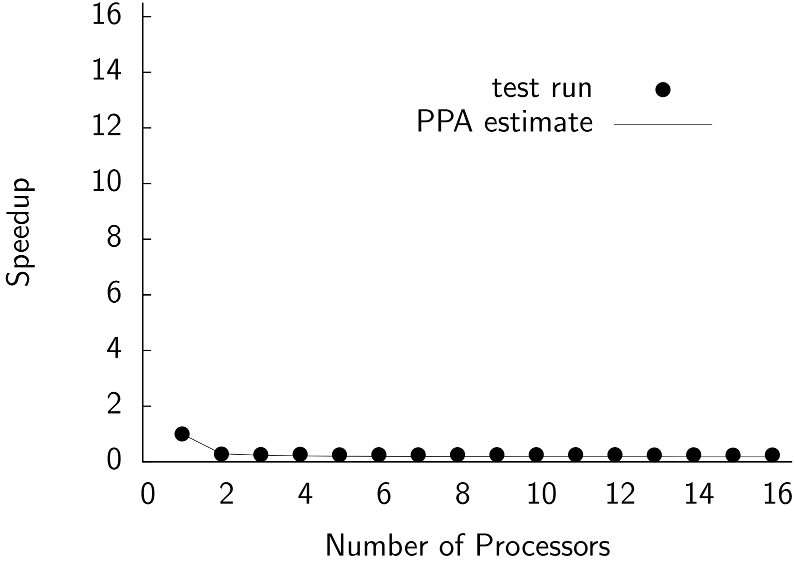
Code:

```
const int N = 1000 * 1000;

void inner_parallel()
{
    for (int i = 0; i < N; ++i)
        cilk_for (int j = 0; j < 4; ++j)
            fib(10); /* do some work */
}
```

Expectations:

- The inner loop does 4 things in parallel. The parallelism should be about 4.
- The PPA says that the parallelism is 3.6.
- We should see some speedup.

“Speedup” of `inner_parallel()`



Interchanging loops

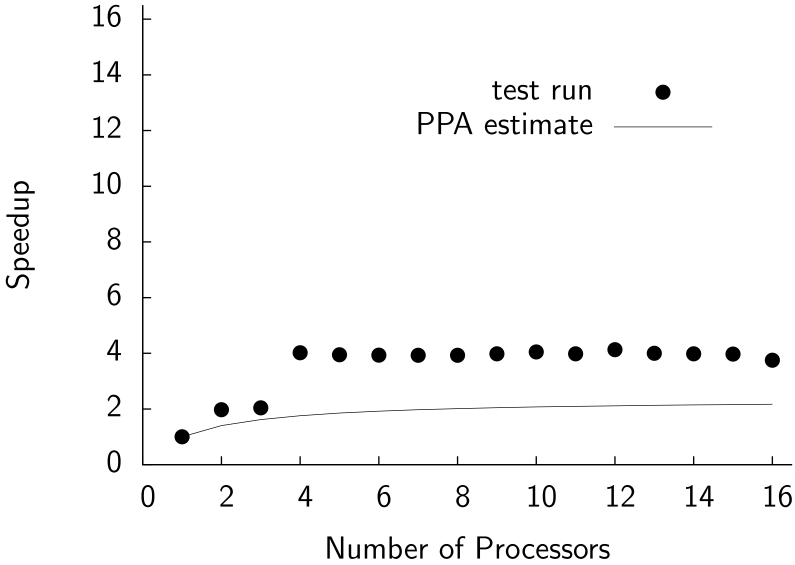
Code:

```
const int N = 1000 * 1000;

void outer_parallel()
{
    cilk_for (int j = 0; j < 4; ++j)
        for (int i = 0; i < N; ++i)
            fib(10); /* do some work */
}
```

Expectations:

- The outer loop does 4 things in parallel. The parallelism should be about 4.
- The PPA says that the parallelism is 4.
- Same as the previous program, which didn't work.

Speedup of `outer_parallel()`



Parallelism vs. burdened parallelism

Parallelism:

The best speedup you can hope for.

Burdened parallelism:

Parallelism after accounting for the unavoidable migration overheads.

Depends upon:

- How well we implement the Cilk++ scheduler.
- How you express the parallelism in your program.

The PPA prints the burdened parallelism:

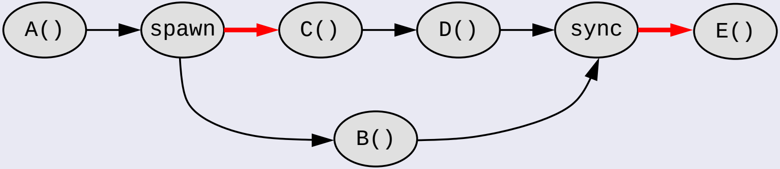
- 0.29 for `inner_parallel()`, 4.0 for `outer_parallel()`.
- In a good program, parallelism and burdened parallelism are about equal.

What is the burdened parallelism?

Code:

```
A();
cilk_spawn B();
C();
D();
cilk_sync;
E();
```

Burdened critical path:



The **burden** is $\Theta(10000)$ cycles (locks, malloc, cache warmup, reducers, etc.)

The burden in our examples

$\Theta(N)$ spawns/syncs on the critical path (large burden):

```
void inner_parallel()
{
    for (int i = 0; i < N; ++i)
        cilk_for (int j = 0; j < 4; ++j)
            fib(10); /* do some work */
}
```

$\Theta(1)$ spawns/syncs on the critical path (small burden):

```
void outer_parallel()
{
    cilk_for (int j = 0; j < 4; ++j)
        for (int i = 0; i < N; ++i)
            fib(10); /* do some work */
}
```

Lessons learned

- Insufficient parallelism yields *no speedup*; high burden yields *slowdown*.
- Many spawns but small parallelism: suspect large burden.
- The PPA helps by printing the burdened span and parallelism.
- The burden can be interpreted as the number of spawns/syncs on the critical path.
- If the burdened parallelism and the parallelism are approximately equal, your program is ok.

Conclusion

We have learned to identify and address these problems:

- High overhead due to small grain size in `cilk_for` loops.
- Insufficient parallelism.
- Insufficient memory bandwidth.
- Insufficient burdened parallelism.