Parallel & Distributed Computing

Performance Optimization in OpenMP

Lecture 6, Spring 2014

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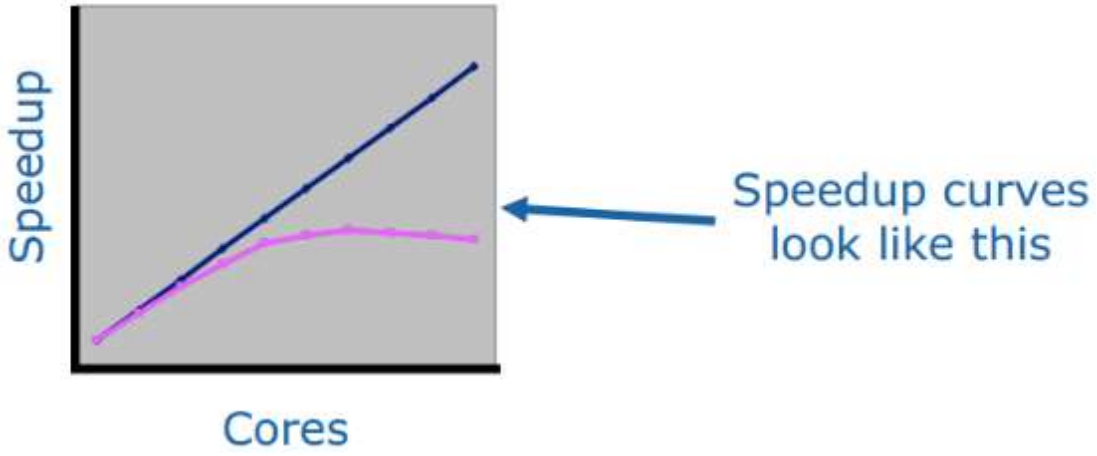
Outline

- Define speedup and efficiency
  - Use Amdahl's Law to predict maximum speedup
- Techniques for Performance Optimization of Parallel Programs
  - Rule of thumb
    - Start with best sequential algorithm
    - Maximize locality
  - Scheduling
  - Loop transformations
    - Loop fission
    - Loop fusion
    - Loop exchange

Speedup

- Speedup is the ratio between sequential execution time and parallel execution time
- For example, if the sequential program executes in 6 seconds and the parallel program executes in 2 seconds, the speedup is 3X



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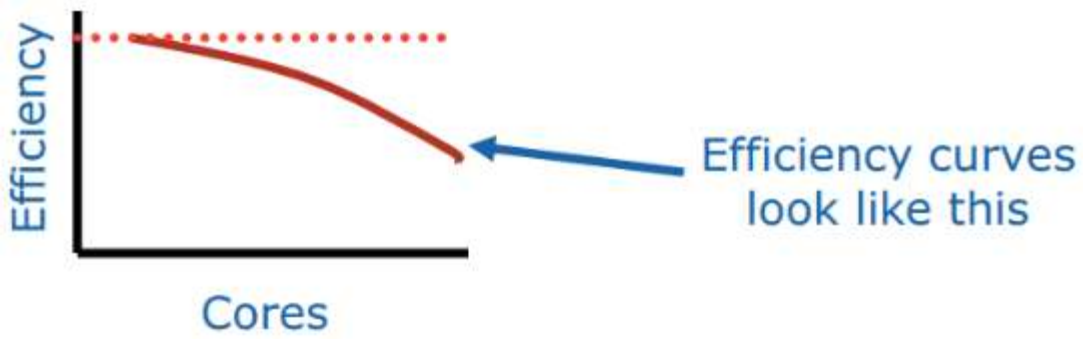
Efficiency

- **Efficiency**
  - **A measure of core utilization**
  - **Speedup divided by the number of cores**
- **Example**
  - **Program achieves speedup of 3 on 4 cores**
  - **Efficiency is 3/4 = 75%**



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Speedup Example

- **Painting a picket fence**
  - **30 minutes of preparation (serial)**
  - **1 minute to paint a single picket**
  - **30 minutes of cleanup (serial)**
- **Thus, 300 pickets takes 360 minutes (serial time)**

Intel, “Introduction to Parallel Programming,” 2009

Computing Speedup

Number of painters	Time	Speedup
1	30 + 300 + 30 = 360	1.0X
2	30 + 150 + 30 = 210	1.7X
10	30 + 30 + 30 = 90	4.0X
100	30 + 3 + 30 = 63	5.7X
∞	30 + 0 + 30 = 60	6.0X

Intel, "Introduction to Parallel Programming," 2009

Efficiency Example

Number of painters	Time	Speedup	Efficiency
1	360	1.0X	100%
2	30 + 150 + 30 = 210	1.7X	85%
10	30 + 30 + 30 = 90	4.0X	40%
100	30 + 3 + 30 = 63	5.7X	5.7%
∞	30 + 0 + 30 = 60	6.0X	very low

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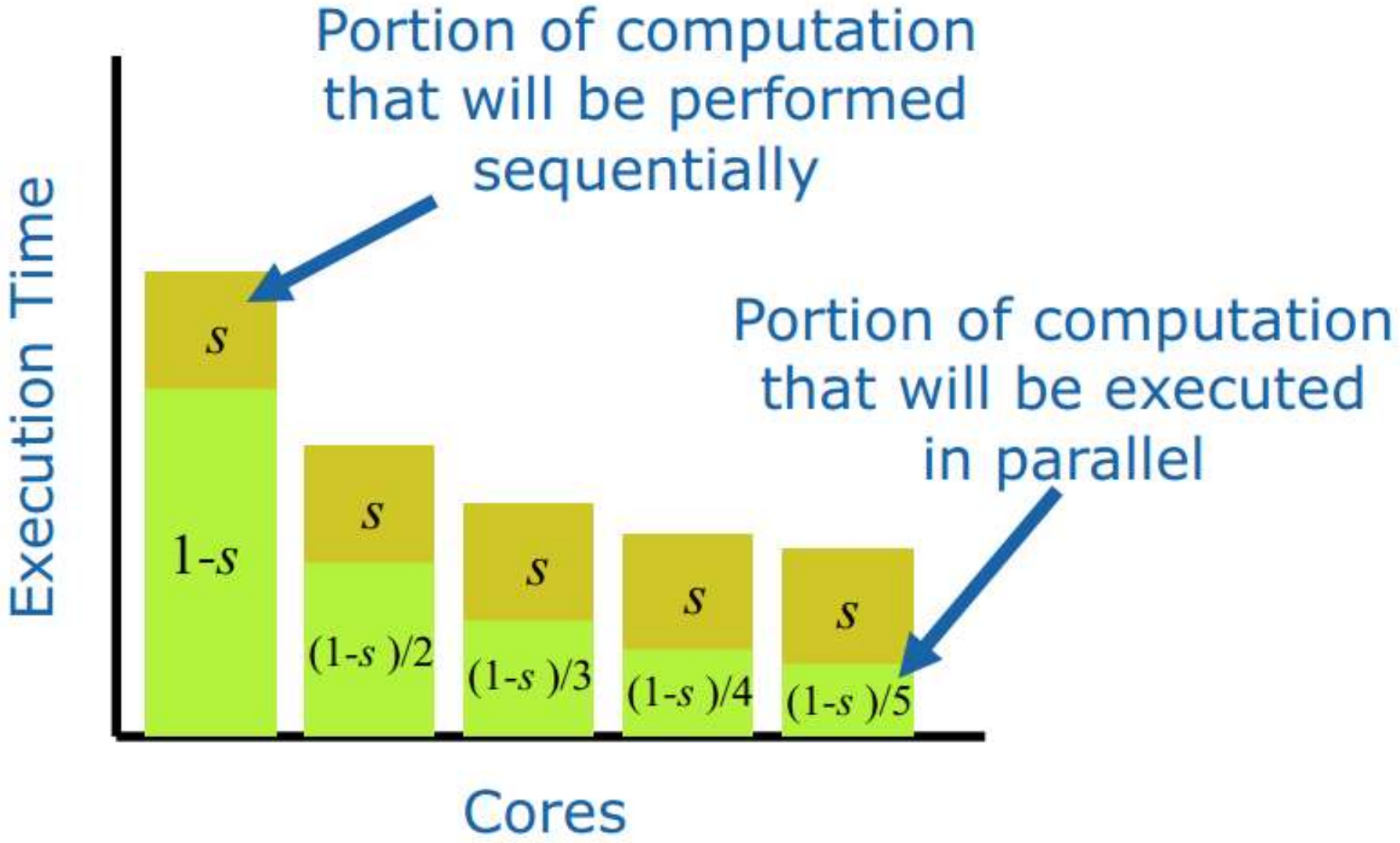
Idea Behind Amdahl's Law



Intel, "Introduction to Parallel Programming," 2009

Derivation of Amdahl's Law

- **Speedup is ratio of execution time on 1 core to execution time on p cores**
- **Execution time on 1 core is s + (1-s)**
- **Execution time on p cores is at least s + (1-s)/p**

$$\psi \le \frac{s + (1-s)}{s + (1-s)/p} = \frac{1}{s + (1-s)/p}$$

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Amdahl's Law is Too Optimistic

- **Amdahl's Law ignores parallel processing overhead**
- **Examples of this overhead include time spent creating and terminating threads**
- **Parallel processing overhead is usually an increasing function of the number of cores (threads)**

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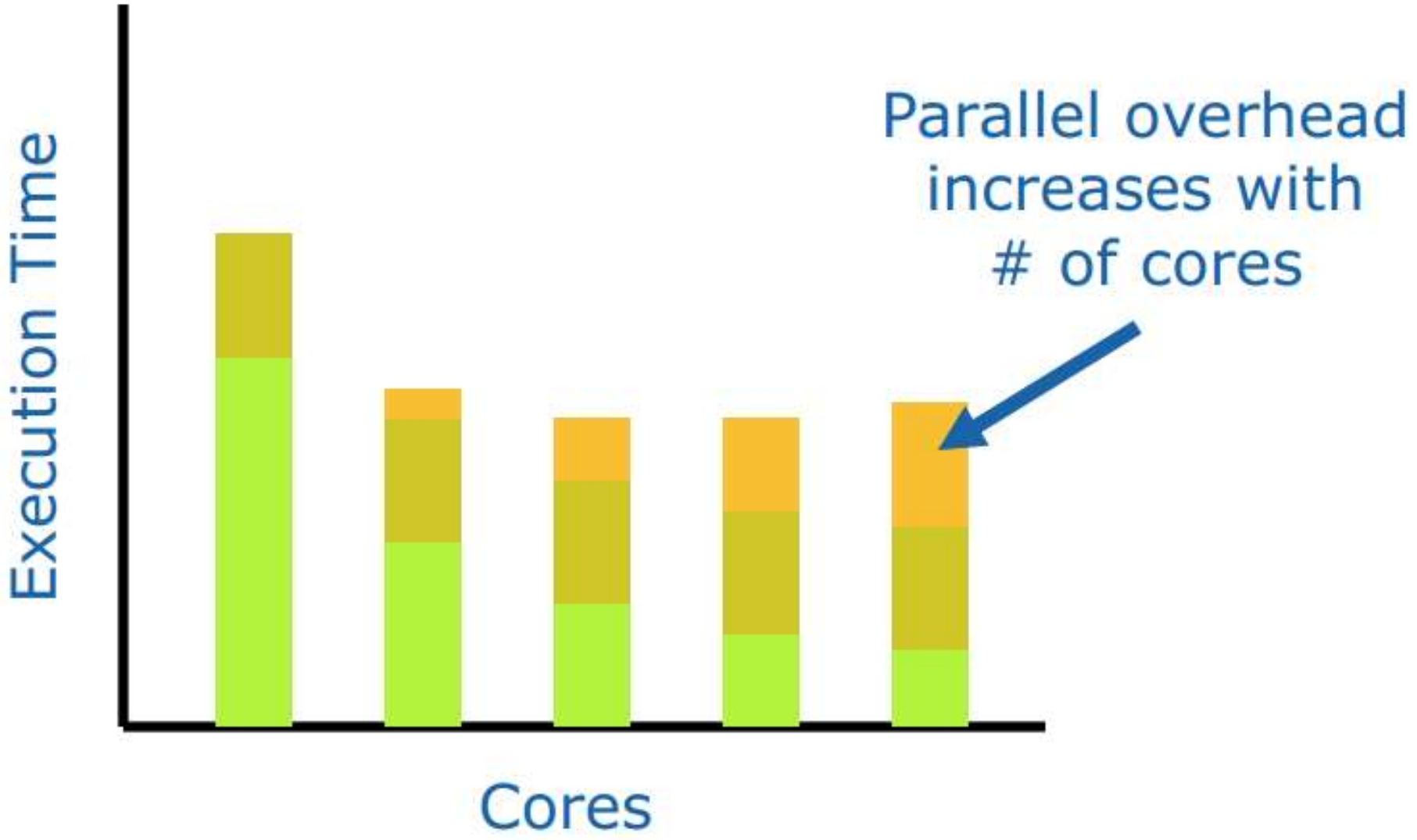
Graph with Parallel Overhead Added



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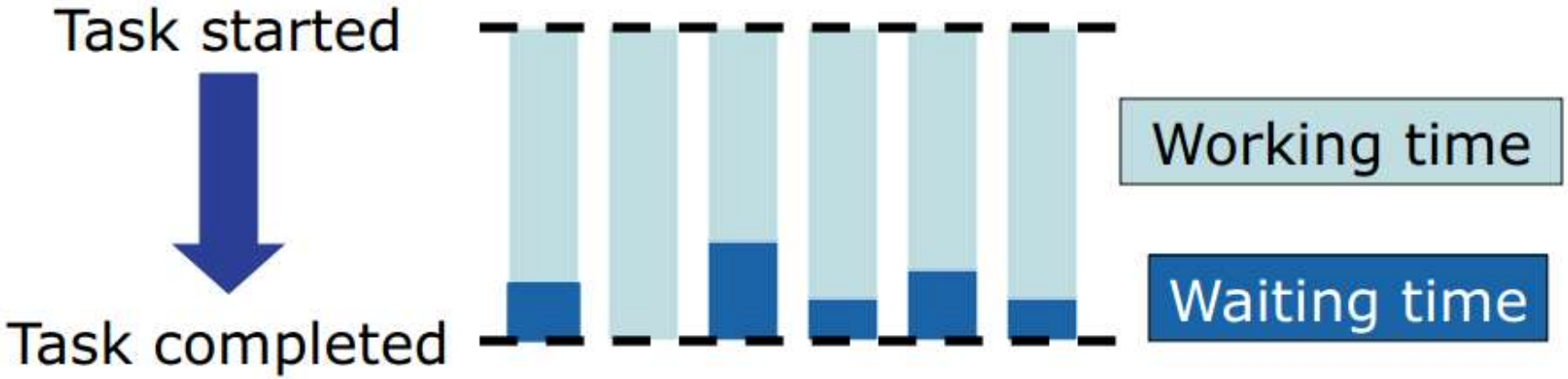
Other Optimistic Assumptions

- Amdahl's Law assumes that the computation divides evenly among the cores
- In reality, the amount of work does not divide evenly among the cores
- Core waiting time is another form of overhead



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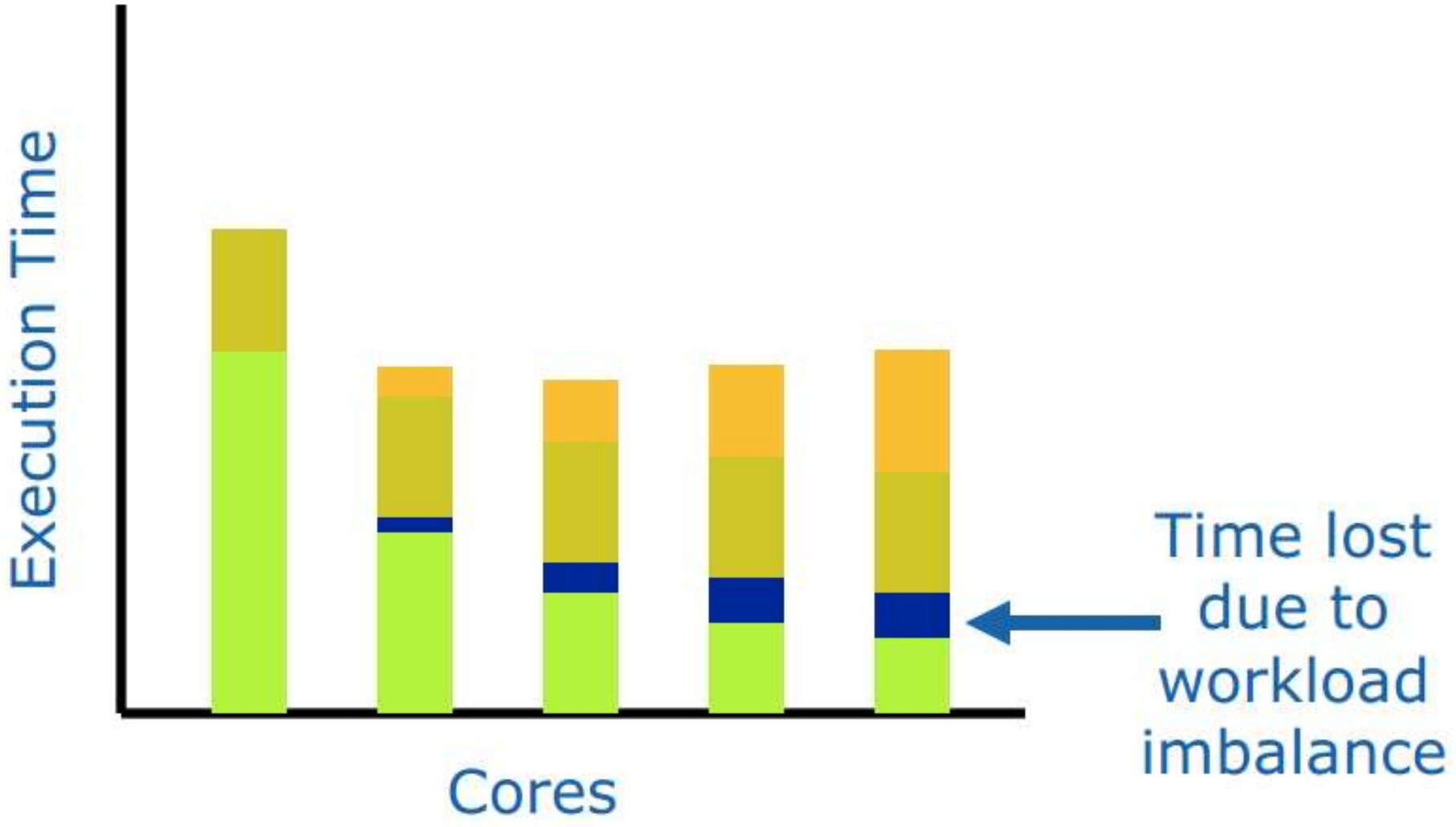
Graph with Workload Imbalance Added



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Using Amdahl's Law

- **Program executes in 5 seconds**
- **Profile reveals 80% of time spent in function alpha, which we can execute in parallel**
- **What would be maximum speedup on 2 cores?**

$$\psi \leq \frac{1}{0.2 + (1-0.2)/2} = \frac{1}{0.6} \approx 1.67$$

- **New execution time ≥ 5 sec / 1.67 = 3 seconds**

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More General Speedup Formula

n	problem size
p	number of cores
$\psi(n,p)$	Speedup for problem (of size n on p cores)
$\sigma(n)$	Time spent in sequential portion of code
$\varphi(n)$	Time spent in parallel portion of code
$\kappa(n,p)$	Parallel overhead

$$\psi(n,p) \leq \frac{\sigma(n)+\varphi(n)}{\sigma(n)+\varphi(n)/\,p+\kappa(n,p)}$$

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Amdahl's Law: Maximum Speedup

$$\psi(n,p) \leq \frac{\sigma(n)+\varphi(n)}{\sigma(n)+\varphi(n)/p+\kappa(n,p)}$$

Assumes parallel work divides perfectly among available cores

This term is set to 0

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The Amdahl Effect

$$\psi(n,p) \le \frac{\sigma(n)+\varphi(n)}{\sigma(n)+\varphi(n)/p+\kappa(n,p)}$$

As $n \to \infty$ these terms dominate

Speedup is an increasing function of problem size

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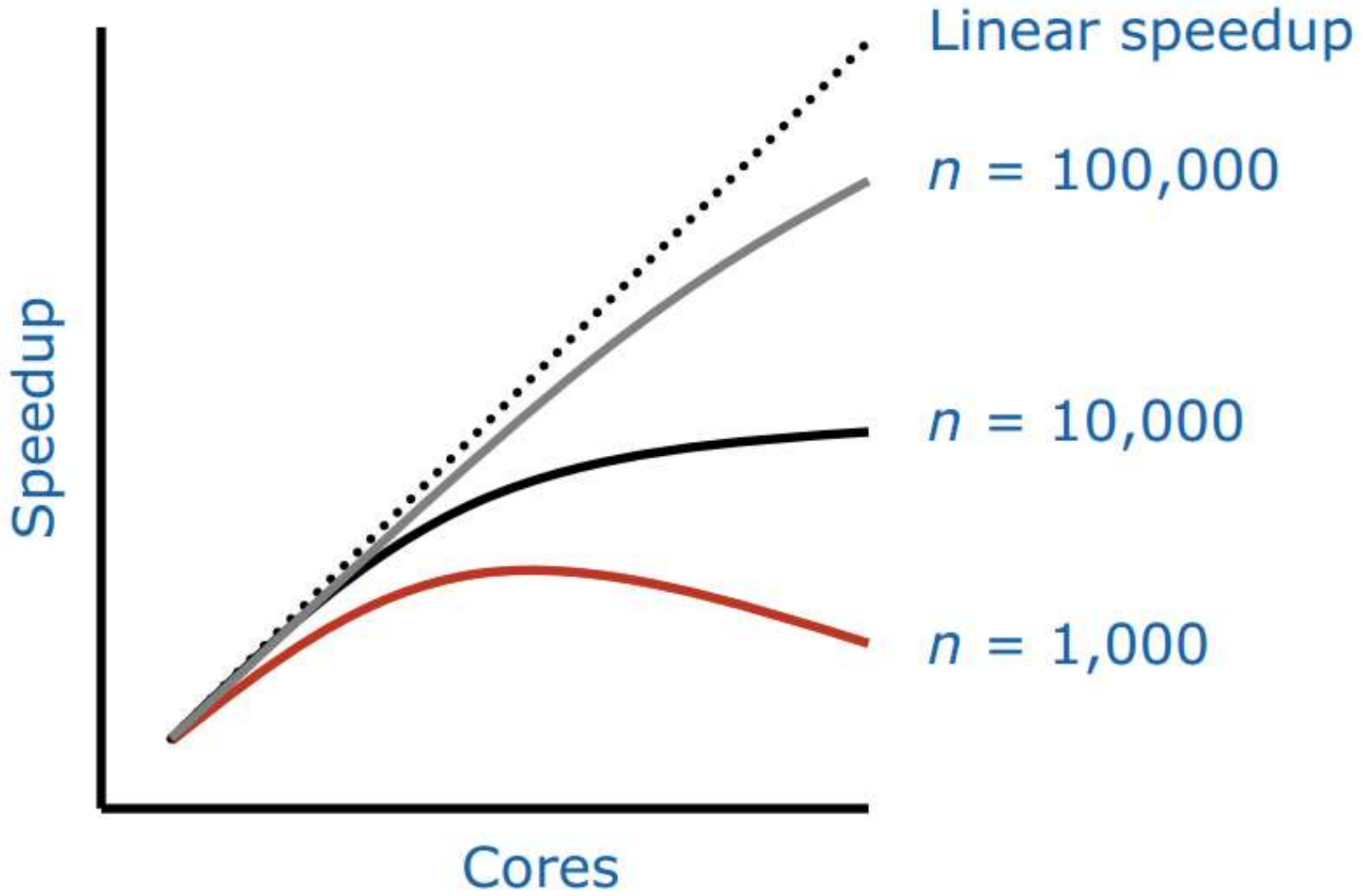
Illustration of the Amdahl Effect



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Superlinear Speedup

- **According to our general speedup formula, the maximum speedup a program can achieve on p cores is p**
- **Superlinear speedup is the situation where speedup is greater than the number of cores used**
  - **It means the computational rate of cores is faster when the parallel program is executing**
  - **Superlinear speedup is usually caused because the cache hit rate of the parallel program is faster**

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Start with Best Sequential Algorithm

- Don't confuse "speedup" with "speed"
- Speedup: ratio of program's execution time on 1 core to its execution time on p cores
- What if start with inferior sequential algorithm?
- Naïve, higher complexity algorithms
  - Easier to make parallel
  - Usually don't lead to fastest parallel algorithm

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Start with Best Sequential Algorithm

Suppose we want to compute 1 + 2 + 3 + ... + n

The Parallel Way

```
 1 +  2 +  3.. + 10
11 + 12 + 13.. + 20
21 + 22 + 23.. + 30
31 + 32 + 33.. + 40
         .
         .
         .
```

And then we add up the partial sums. ***O(n)*** additions, divided by ***p*** processors.

We can use hundreds or thousands of processors, and keep them all busy.

The Serial Way

```
n*(n+1)/2
```

No matter what the value of ***n***, the serial way takes three instructions, and is ***O(1)***. There's some parallelism here, but at minimum, it's two steps.

The serial way is
faster
lower power
less hardware
no compiler grief.

Which one would you buy?

P. Madden, "Why Parallel Computers Fails Commercially," DAC 2011.

Maximize Locality

- **Temporal locality**
  - **If a processor accesses a memory location, there is a good chance it will revisit that memory location soon**
- **Data locality**
  - **If a processor accesses a memory location, there is a good chance it will visit a nearby location soon**
- **Programs tend to exhibit locality because they tend to have loops indexing through arrays**
- **Principle of locality makes cache memory worthwhile**

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Parallel Processing and Locality

- **Multiple cores ⇒ multiple caches**
  - **When a core writes a value, the system must ensure no core tries to reference an obsolete value (cache coherence problem)**
  - **A write by one core can cause the invalidation of another core's copy of cache line, leading to a cache miss**
- **Rule of thumb: Better to have different cores manipulating totally different chunks of arrays**
- **We say a parallel program has good locality if core's memory writes tend not to interfere with the work being done by other cores**

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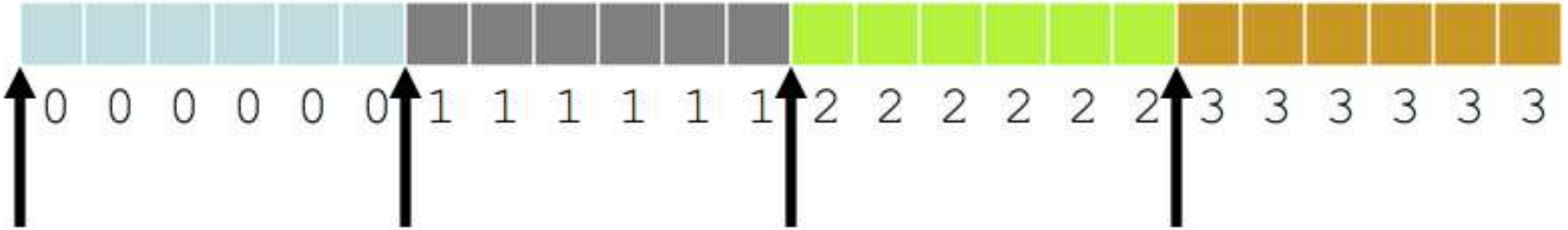
Example: Array Initialization

```
for (i = 0; i < N; i++) a[i] = 0;
```

Terrible allocation of work to processors

Better allocation of work to processors...



unless sub-arrays map to same cache lines!

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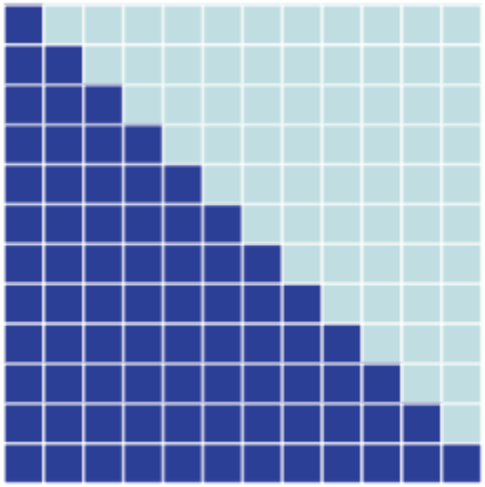
Loop Scheduling Example

```
for (int i = 0; i < 12; i++)
    for (int j = 0; j <= i; j++)
        a[i][j] = …;
```



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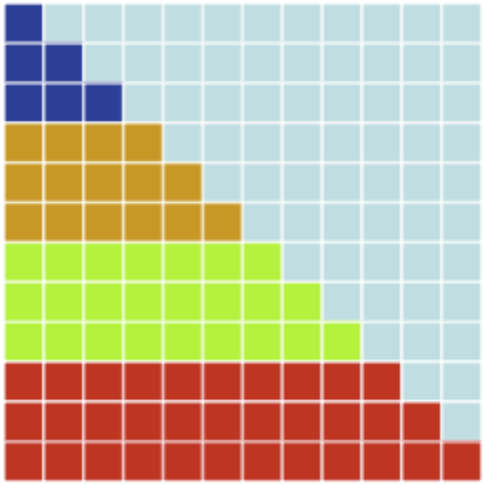
Loop Scheduling Example

```
#pragma omp parallel for
for (int i = 0; i < 12; i++)
    for (int j = 0; j <= i; j++)
        a[i][j] = …;
```



Typically, the iterations are divided by the number of threads and assigned as chunks to a thread

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Loop Scheduling

- **Loop schedule**
  - **How loop iterations are assigned to threads**
  - **Static schedule**
    - **Iterations assigned to threads before execution of loop**
  - **Dynamic schedule**
    - **Iterations assigned to threads during execution of loop**
- **The OpenMP *schedule* clause affects how loop iterations are mapped onto threads**

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The schedule **Clause**

- *schedule (static [, chunk])*
  - **Blocks of iterations of size "chunk" to threads**
  - **Round robin distribution**
  - **Low overhead, may cause load imbalance**
- **Best used for predictable and similar work per iteration**

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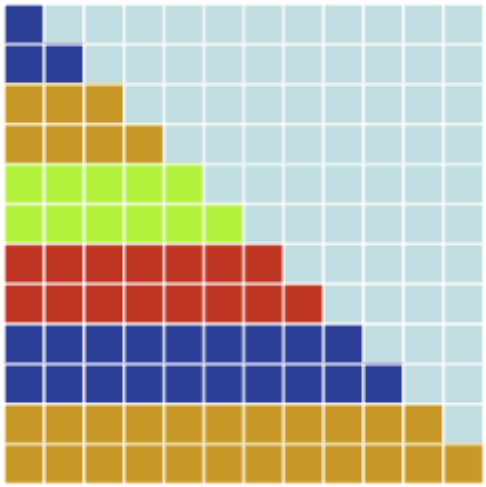
Loop Scheduling Example

```
#pragma omp parallel for schedule(static, 2)
for (int i = 0; i < 12; i++)
    for (int j = 0; j <= i; j++)
        a[i][j] = …;
```



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The schedule **Clause**

- *schedule (dynamic [, chunk])*
  - **Threads grab "chunk" iterations**
  - **When done with iterations, thread requests next set**
  - **Higher threading overhead, can reduce load imbalance**
- **Best used for unpredictable or highly variable work**

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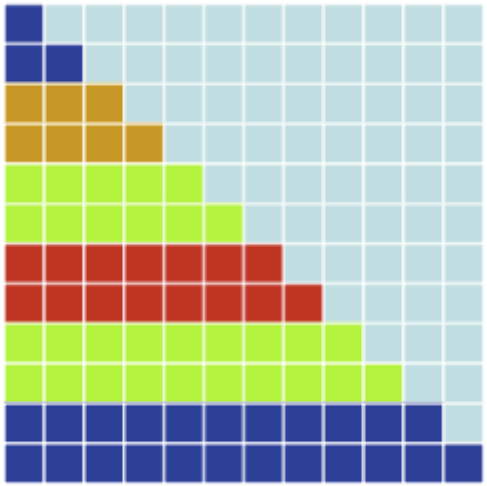
Loop Scheduling Example

```
#pragma omp parallel for schedule(dynamic, 2)
for (int i = 0; i < 12; i++)
    for (int j = 0; j <= i; j++)
        a[i][j] = …;
```



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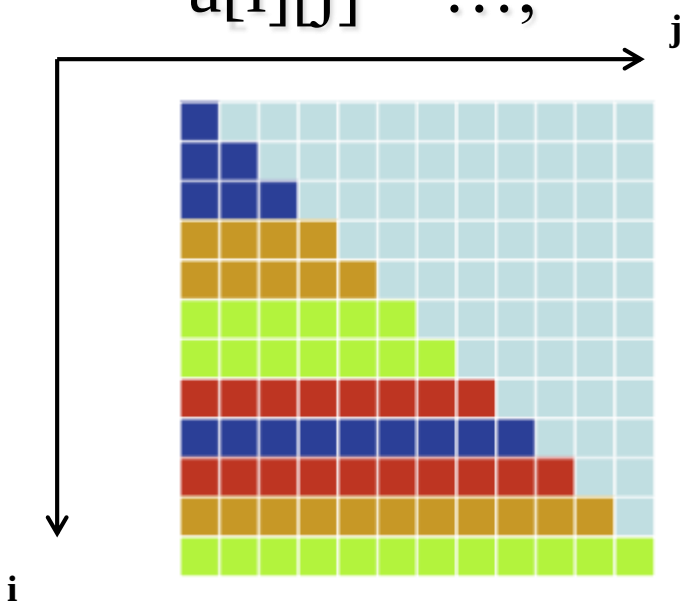
The schedule Clause

- *schedule (guided [, chunk])*
  - **Dynamic schedule starting with large block**
  - **Size of the blocks shrink; no smaller than "chunk"**
  - **The initial block is proportional to**
    - **number_of_iterations / number_of_threads**
  - **Subsequent blocks are proportional to**
    - **number_of_iterations_remaining / number_of_threads**
- **Best used as a special case of dynamic to reduce scheduling overhead when the computation gets progressively more time consuming**

Intel, "Introduction to Parallel Programming," 2009

Loop Scheduling Example

```
#pragma omp parallel for schedule(guided)
for (int i = 0; i < 12; i++)
    for (int j = 0; j <= i; j++)
        a[i][j] = …;
```



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Loop Transformations

- **Loop fission**
- **Loop fusion**
- **Loop exchange**

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Loop Fission

- Begin with single loop having loop-carried dependence
- Split loop into two or more loops
- New loops can be executed in parallel

Intel, “Introduction to Parallel Programming,” 2009

Before Loop Fission

```
float *a, *b;
for (int i = 1; i < N; i++) {
    // perfectly parallel
    if (b[i] > 0.0) a[i] = 2.0;
    else a[i] = 2.0 * fabs(b[i]);
    // loop-carried dependence
    b[i] = a[i-1];
}
```

Intel, “Introduction to Parallel Programming,” 2009

After Loop Fission

```
float *a, *b;
#pragma omp parallel
{
#pragma omp for
    for (int i = 1; i < N; i++) {
        if (b[i] > 0.0) a[i] = 2.0;
        else a[i] = 2.0 * fabs(b[i]);
    }
#pragma omp for
    for (int i = 1; i < N; i++) b[i] = a[i-1];
}
```

Intel, “Introduction to Parallel Programming,” 2009

Loop Fission and Locality

- Another use of loop fission is to increase data locality
- Before fission, nested loops reference too many data values, leading to poor cache hit rate
- Break nested loops into multiple nested loops
- New nested loops have higher cache hit rate

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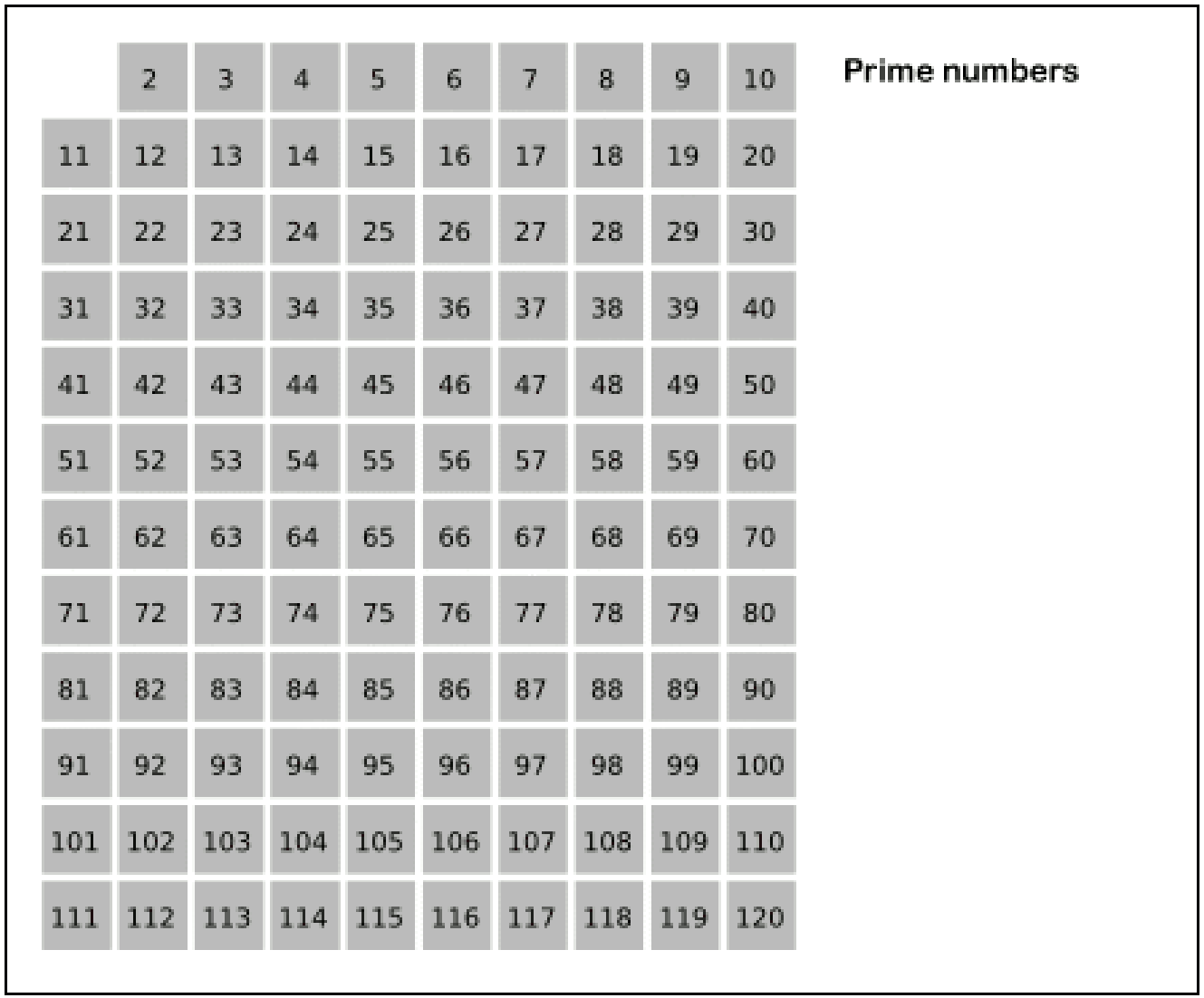
Example: Sieve of Eratosthenes



	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100
101	102	103	104	105	106	107	108	109	110
111	112	113	114	115	116	117	118	119	120

Source: Wikipedia, http://en.wikipedia.org/wiki/Sieve_of_Eratosthenes

Before Fission

```
for (int i = 0; i < list_len; i++)
    for (int j = 2*prime[i]; j < N; j += prime[i])
        marked[j] = 1;
```

Intel, “Introduction to Parallel Programming,” 2009

After Fission

```
for (int k = 0; k < N; k+= CHUNK_SIZE)
    for (int i = 0; i < list_len; i++) {
        start = f(prime[i], k);
        end = g(prime[i], k);
        for (int j = start; j < end; j += prime[i])
            marked[j] = 1;
    }
```

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Loop Fusion

- The opposite of loop fission
- Combine loops increase grain size

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Before Loop Fusion

```
float *a, *b, x, y;

…

for (int i = 0; i < N; i++) a[i] = foo(i);

x = a[N-1] – a[0];

for (int i = 0; i < N; i++) b[i] = bar(a[i]);

y = x * b[0] / b[N-1];
```

- **Assume functions *foo* and *bar* are side-effect free**

Intel, “Introduction to Parallel Programming,” 2009

After Loop Fusion

```
#pragma omp parallel for
for (int i = 0; i < N; i++) {
      a[i] = foo(i);
      b[i] = bar(a[i]);
}
x = a[N-1] – a[0];
y = x * b[0] / b[N-1];
```

- **Now one barrier instead of two**

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Loop Fusion with Replicated Work

- Every thread iteration has a cost
- Example: Barrier synchronization
- Sometimes it's faster for threads to replicate work than to go through a barrier synchronization

Before Work Replication

```
for (int i = 0; i < N; i++) a[i] = foo(i);
x = a[0] / a[N-1];
for (int i = 0; i < N; i++) b[i] = x * a[i];
```

- **Both *for* loops are amenable to parallelization**

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First OpenMP Attempt

```
#pragma omp parallel
{
#pragma omp for
    for (int i = 0; i < N; i++) a[i] = foo(i);
#pragma omp single
    x = a[0] / a[N-1]; // implicit barrier
#pragma omp for
    for (int i = 0; i < N; i++) b[i] = x * a[i];
}
```

- **Synchronization among threads required if *x* is shared and one thread performs assignment**

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After Work Replication

```
#pragma omp parallel private (x)
{
    x = foo(0) / foo(N-1);
#pragma omp for
    for (int i = 0; i < N; i++) {
        a[i] = foo(i);
        b[i] = x * a[i];
    }
}
```

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Loop Fusion Example

```
#define N 23
#define M 1000
…
for (int k = 0; k < N; k++)
    for (int j = 0; j < M; j++)
        w_new[k][j] = DoSomeWork(w[k][j], k, j);
```

- **Prime number of iterations will never be perfectly load balanced**
- **Parallelize inner loop? Are there enough iterations to overcome overhead?**

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Loop Fusion Example

```
#define N 23
#define M 1000
…
for (int kj = 0; kj < N*M; kj++) {
      k = kj / M;
      j = kj % M;
      w_new[k][j] = DoSomeWork(w[k][j], k, j);
}
```

- **Larger number of iterations gives better opportunity for load balance and hiding overhead**
- **DIV and MOD are overhead**

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Loop Exchange (Inversion)

- **Nested *for* loops may have data dependences that prevent parallelization**
- **Exchanging the nesting of *for* loops may**
  - **Expose a parallelizable loop**
  - **Increase grain size**
  - **Improve parallel program's locality**

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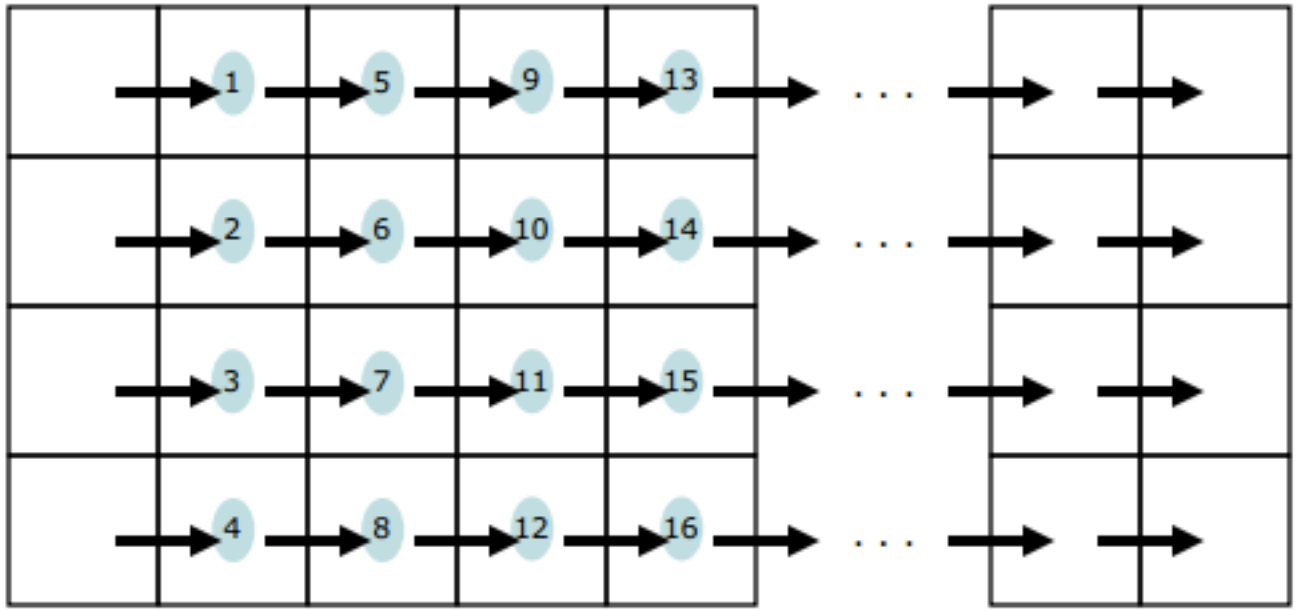
Loop Inversion Example

```
for (int j =1; j < n; j++)
    for (int i = 0; i < m; i++)
        a[i][j] = 2 * a[i][j-1];
```



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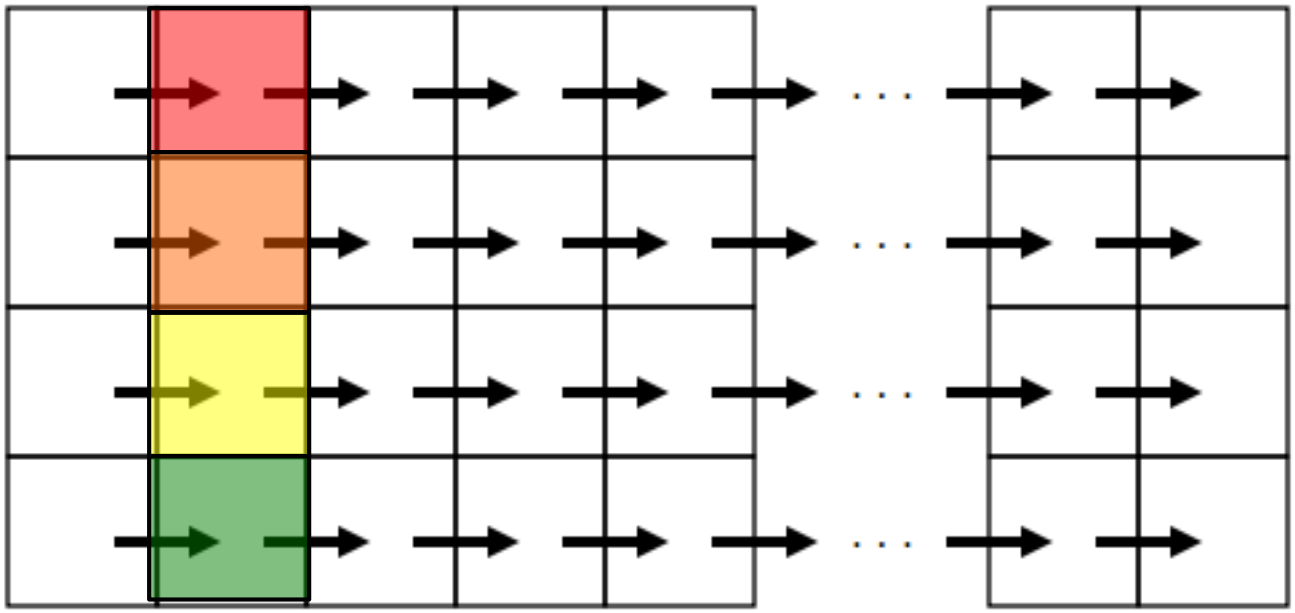
Before Loop Inversion

```
for (int j =1; j < n; j++)
#pragma omp parallel for
    for (int i = 0; i < m; i++)
        a[i][j] = 2 * a[i][j-1];
```



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Before Loop Inversion

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for (int j =1; j < n; j++)
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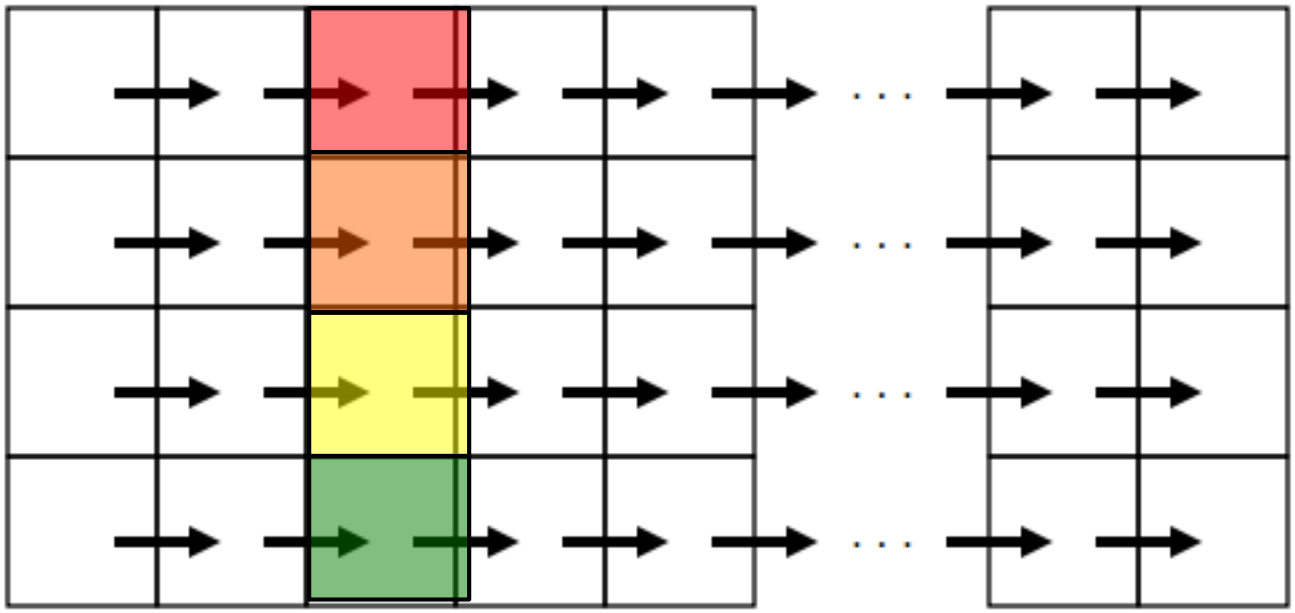

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Before Loop Inversion

```
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#pragma omp parallel for
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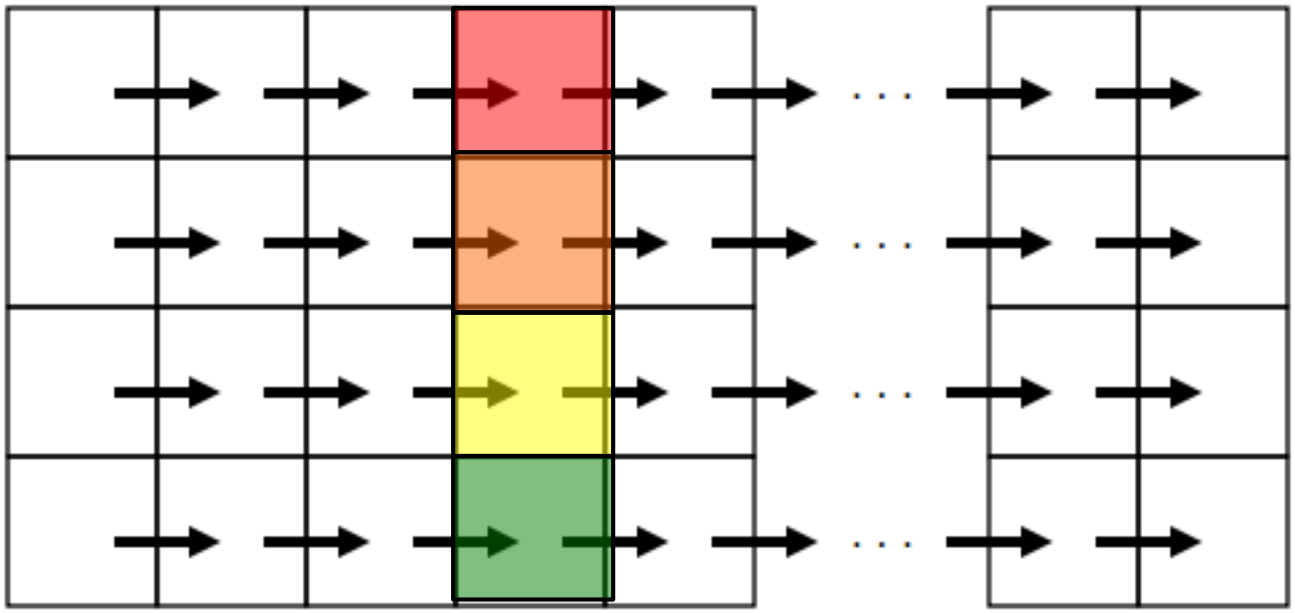
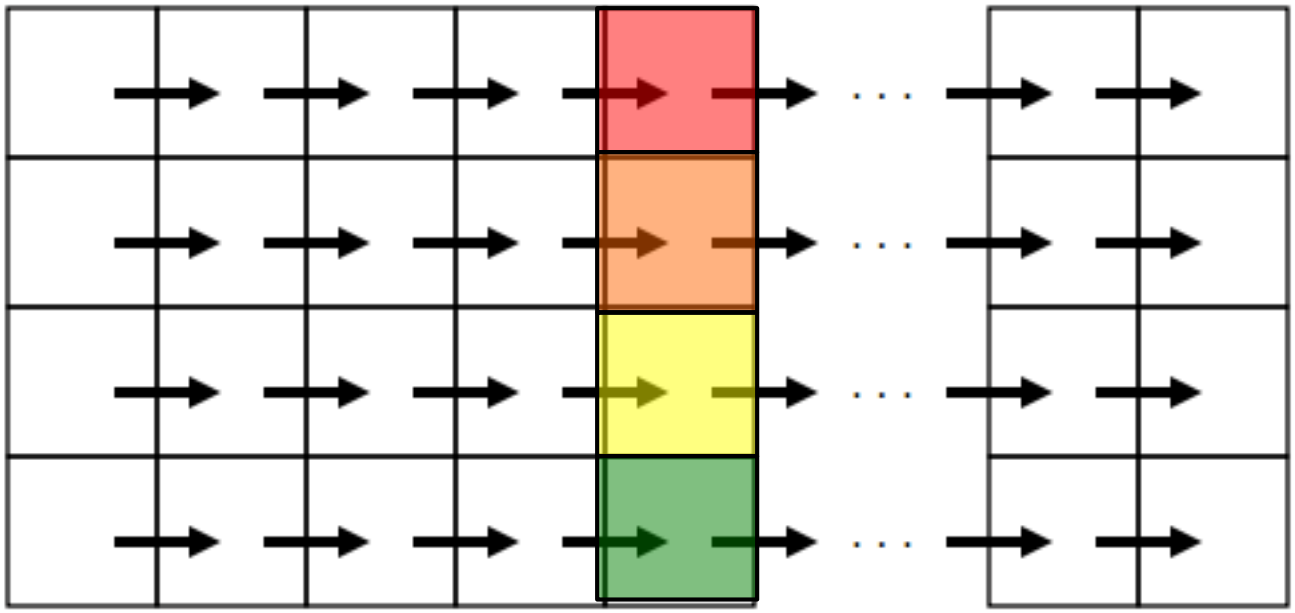
        a[i][j] = 2 * a[i][j-1];
```



Intel, “Introduction to Parallel Programming,” 2009

Before Loop Inversion

```
for (int j =1; j < n; j++)
#pragma omp parallel for
    for (int i = 0; i < m; i++)
        a[i][j] = 2 * a[i][j-1];
```



Intel, “Introduction to Parallel Programming,” 2009

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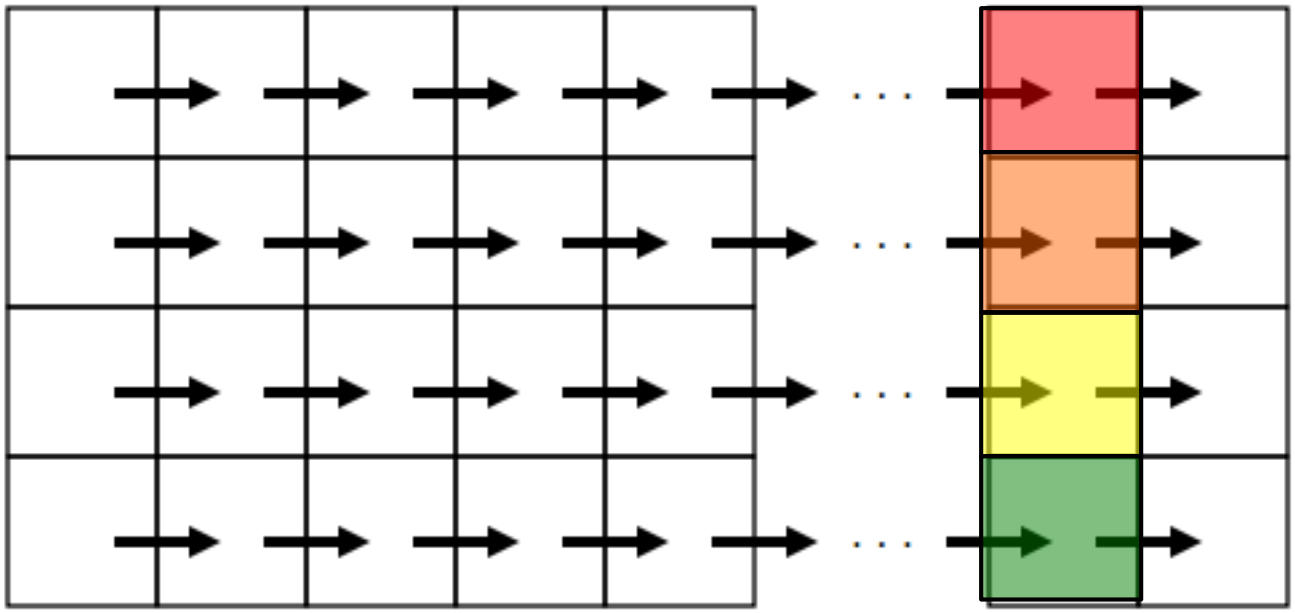

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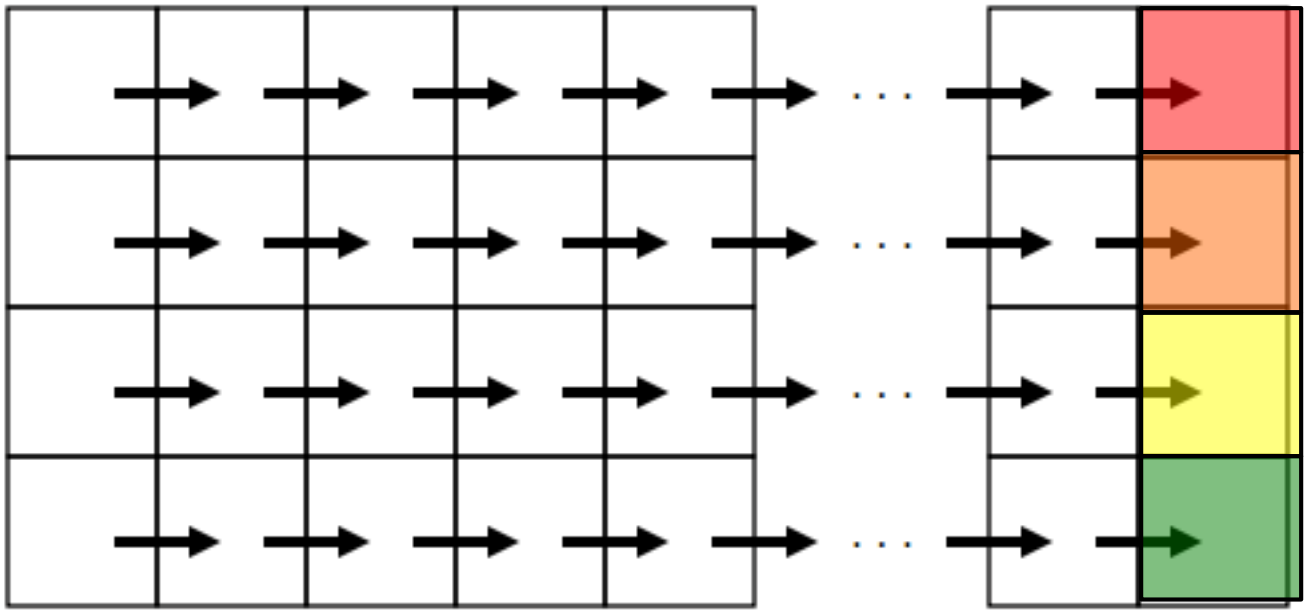

Intel, “Introduction to Parallel Programming,” 2009

After Loop Inversion

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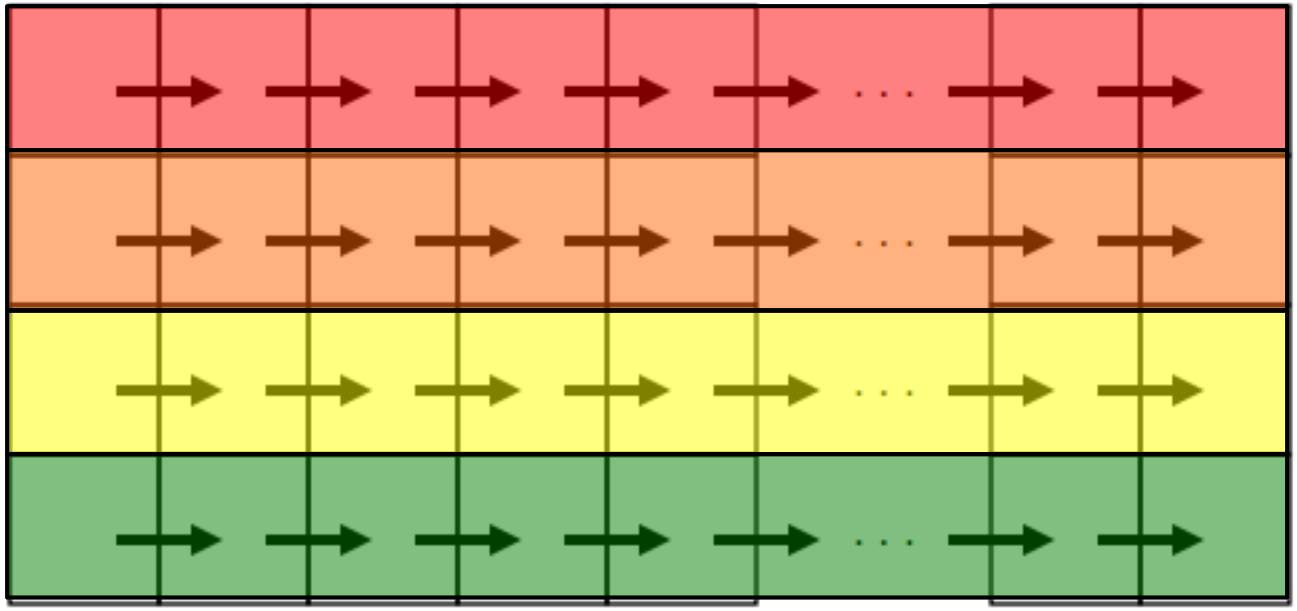
    for (int j =1; j < n; j++)
        a[i][j] = 2 * a[i][j-1];
```



Intel, “Introduction to Parallel Programming,” 2009

Summary

- Define speedup and efficiency
  - Use Amdahl's Law to predict maximum speedup
- Techniques for Performance Optimization of Parallel Programs
  - Rule of thumb
    - Start with best sequential algorithm
    - Maximize locality
  - Scheduling
  - Loop transformations
    - Loop fission
    - Loop fusion
    - Loop exchange