Optimizing for Multicores

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Outline of these lectures

1. Processor implementations
2. Caches and memory system
3. Multiprocessors
4. HW optimizations
5. Multicore processors
6. **SW optimizations**

Optimizing for the memory system: What is the potential gain?

- Latency difference L1$ and mem: ~50x
- Bandwidth difference L1$ and mem: ~20x
- Execute from L1$ instead from mem ==> 50-150x improvement
- At least a factor 2-4x is within reach

Optimizing for cache performance

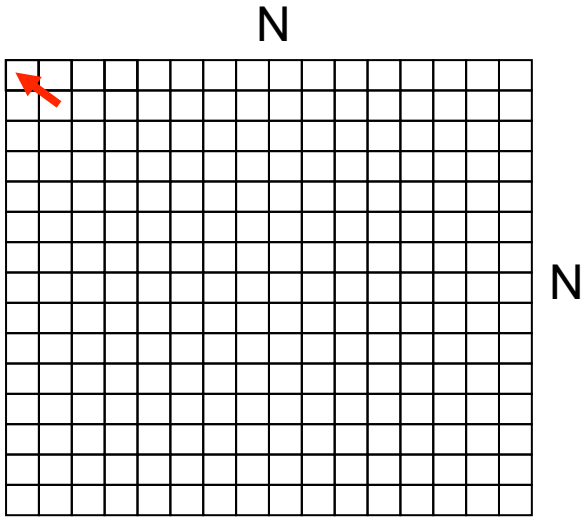
- Keep the active footprint small
- Use the entire cache line once it has been brought into the cache
- Fetch a cache line prior to its usage
- Let the CPU that already has the data in its cache do the job
- …

Final cache lingo slide

- **Miss ratio:** What is the likelihood that a memory access will miss in a cache?
- **Miss rate:** D:o per time unit, e.g. per-second, per-1000-instructions
- **Fetch ratio/rate:** What is the likelihood that a memory access will cause a fetch to the cache [including HW prefetching]
- **Fetch utilization:** What fraction of a cacheline was used before it got evicted
- **Writeback utilization:** What fraction of a cacheline written back to memory contains dirty data
- **Communication utilization:** What fraction of a communicated cacheline is ever used?

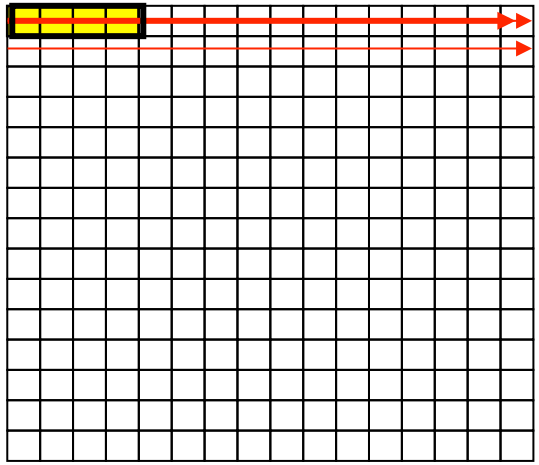
What can go Wrong? A Simple Example…

Perform a diagonal copy 10 times

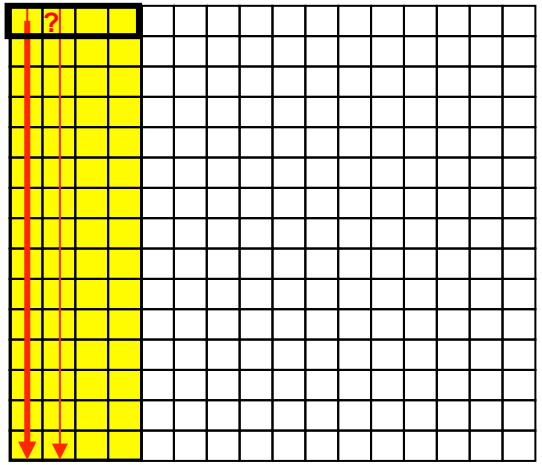


Example: Loop order

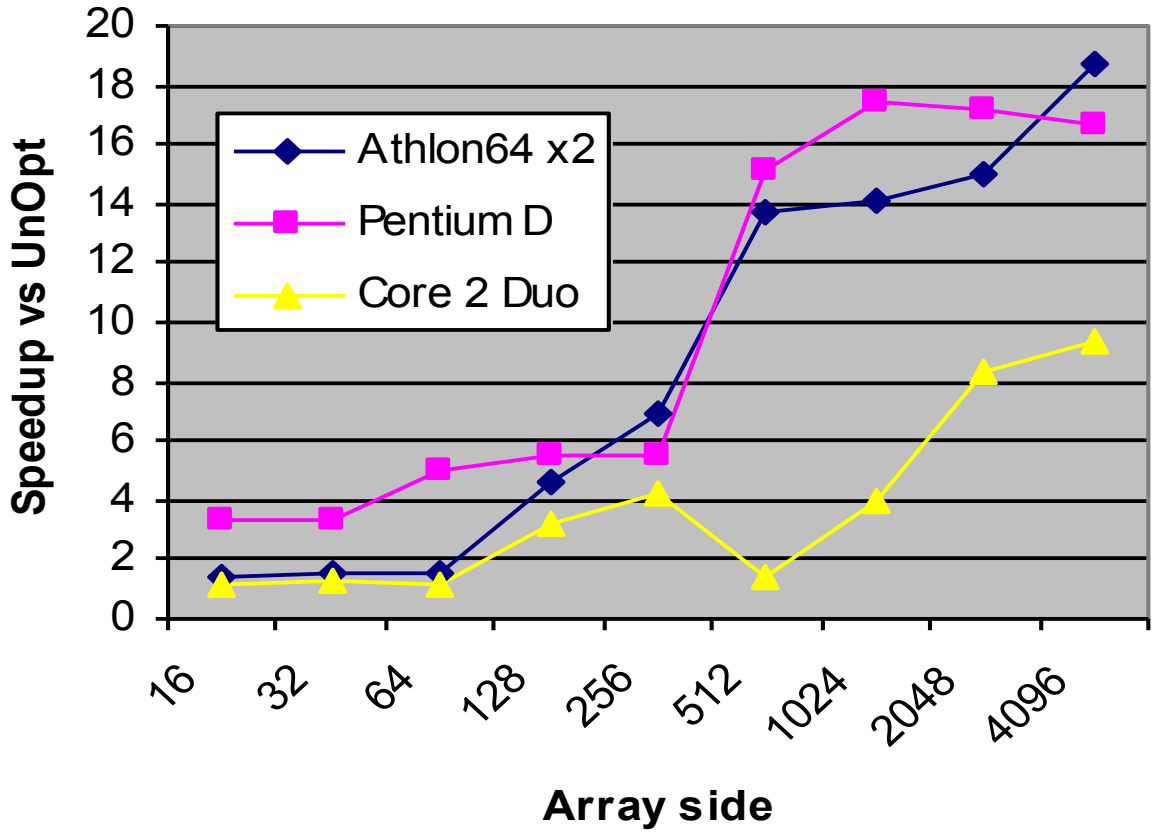
```
//Optimized Example A
for (i=1; i<N; i++) {
  for (j=1; j<N; j++) {
    A[i][j]= A[i+1][j+1];
  }
}
```



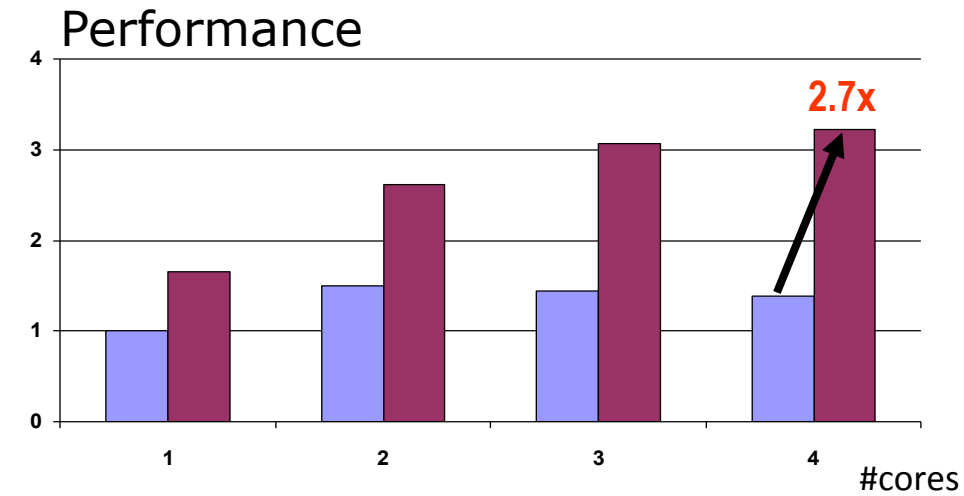
```
//Unoptimized Example A
for (j=1; j<N; j++) {
  for (i=1; i<N; i++) {
    A[i][j] = A[i+1][j+1];
  }
}
```



Performance Difference: Loop order



Example 1: LBM



App: LBM

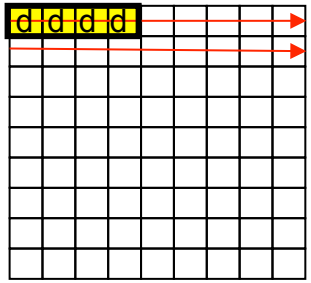
Optimization can be rewarding, but costly…

- Require expert knowledge about MC and architecture
- Weeks of wading through performance data

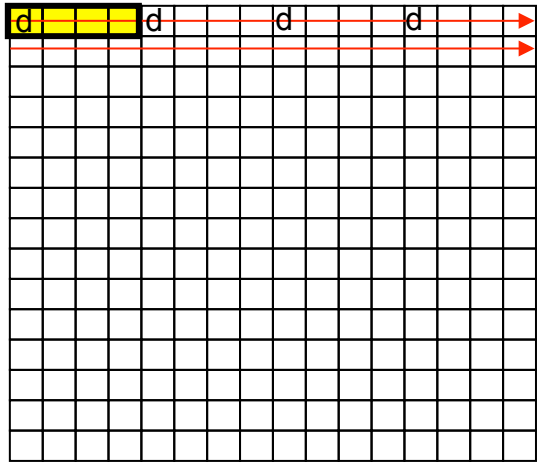
➔This fix required one line of code to change

Example: Sparse data usage

```
//Optimized Example A
for (i=1; i<N; i++) {
  for (j=1; j<N; j++) {
    A_d[i][j]= A_d[i-1][j-1];
  }
}
```

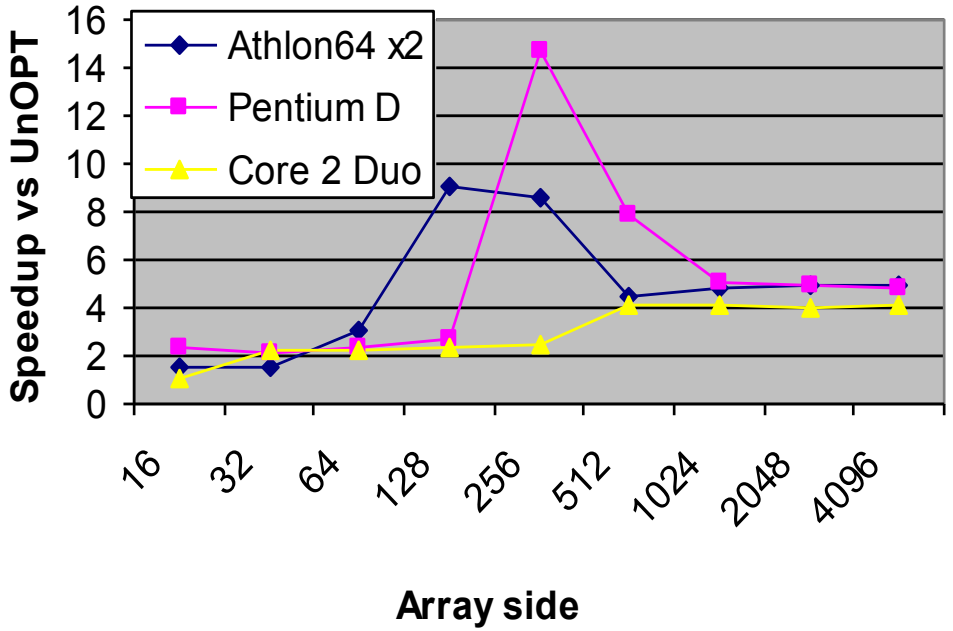



```
//Unoptimized Example A
for (i=1; i<N; i++) {
  for (j=1; j<N; j++) {
    A[i][j].d = A[i-1][j-1].d;
  }
}
```

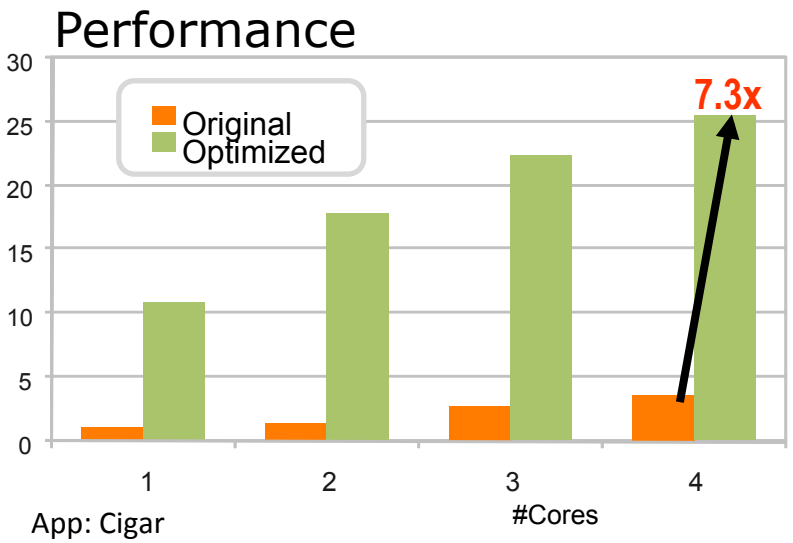



```
struct vec_type
{
        char a;
        char b;
        char c;
        char d;
};
```

Performance Difference: Sparse Data



Example 2: The Same Application Optimized



Looks like a perfect scalable application!

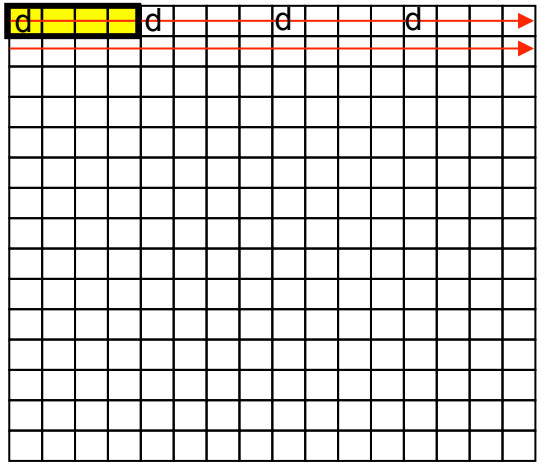
Are we done?

➔ Duplicate one data structure

Example: Sparse data allocation

```
sparse_rec sparse [HUGE];

for (int j = 0; j < HUGE; j++)
{
    sparse[j].a = 'a'; sparse[j].b = 'b'; sparse[j].c = 'c'; sparse[j].d = 'd'; sparse[j].e = 'e';
    sparse[j].f1 = 1.0; sparse[j].f2 = 1.0; sparse[j].f3 = 1.0; sparse[j].f4 = 1.0; sparse[j].f5 = 1.0;
}
```




```
struct sparse_rec
{
            // size 80B
            char a;
            double f1;
            char b;
            double f2;
            char c;
            double f3;
            char d;
            double f4;
            char e;
            double f5;
};
```

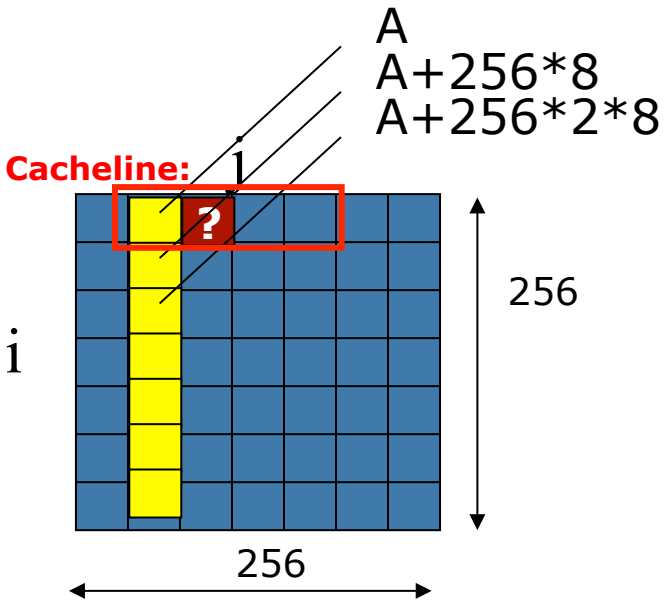
```
struct dense_rec
{
            //size 48B
            double f1;
            double f2;
            double f3;
            double f4;
            double f5;
            char a;
            char b;
            char c;
            char d;
            char e;
};
```

Loop Merging

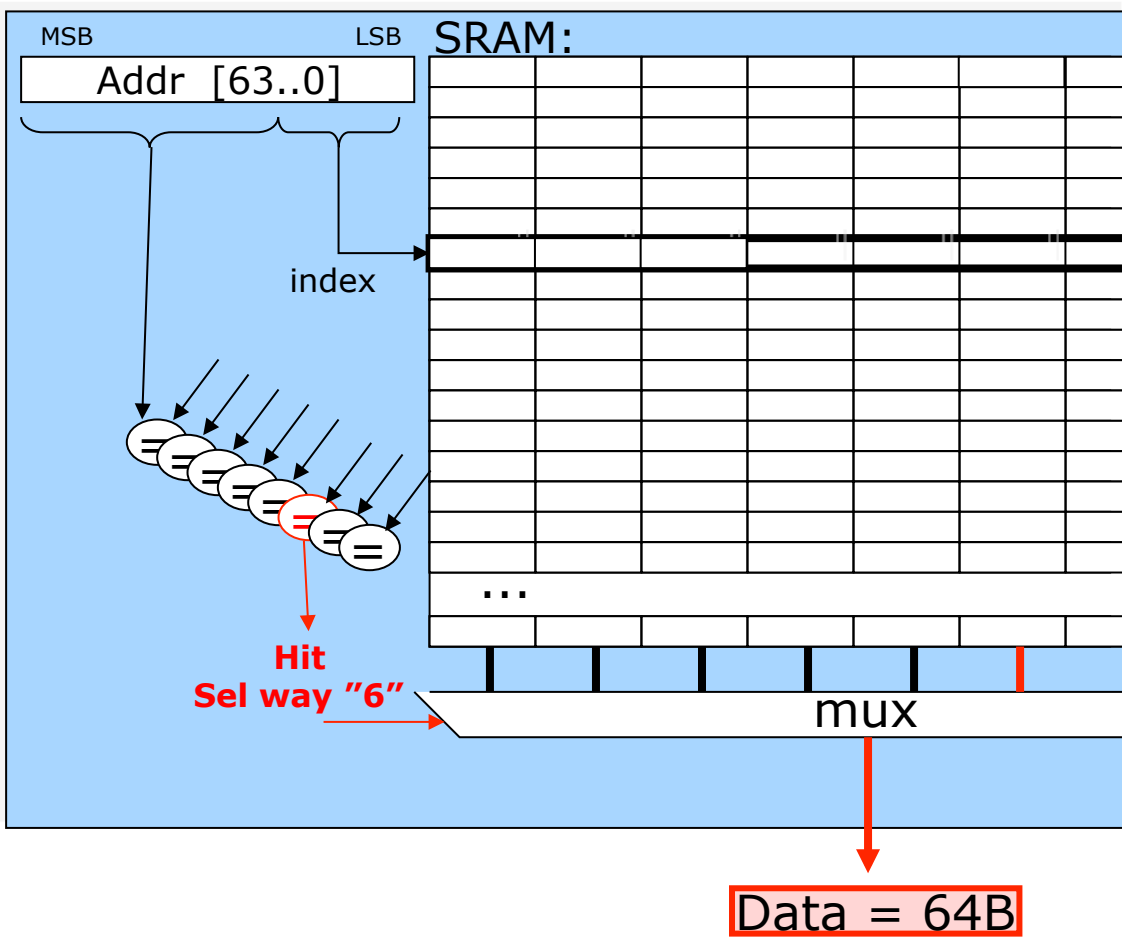
```
/* Unoptimized */
for (i = 0; i < N; i = i + 1)
   for (j = 0; j < N; j = j + 1)
        a[i][j] = 2 * b[i][j];
for (i = 0; i < N; i = i + 1)
   for (j = 0; j < N; j = j + 1)
        c[i][j] = K * b[i][j] + d[i][j]/2

/* Optimized */
for (i = 0; i < N; i = i + 1)
   for (j = 0; j < N; j = j + 1)
        a[i][j] = 2 * b[i][j];
        c[i][j] = K * b[i][j] + d[i][j]/2;
```

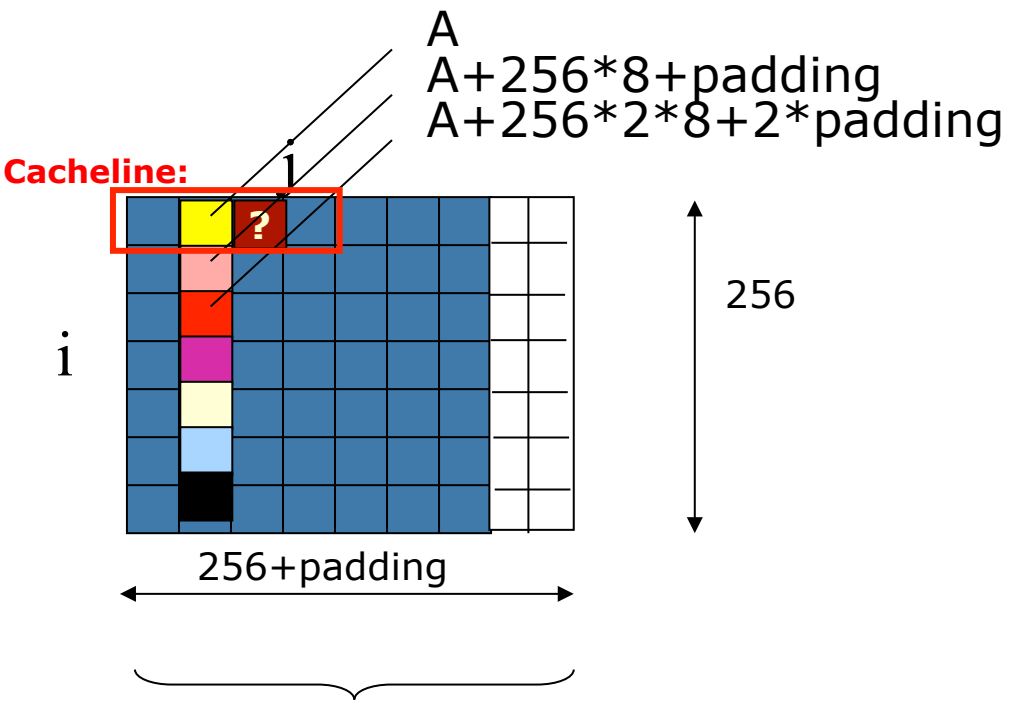
Padding of data structures



Generic Cache:

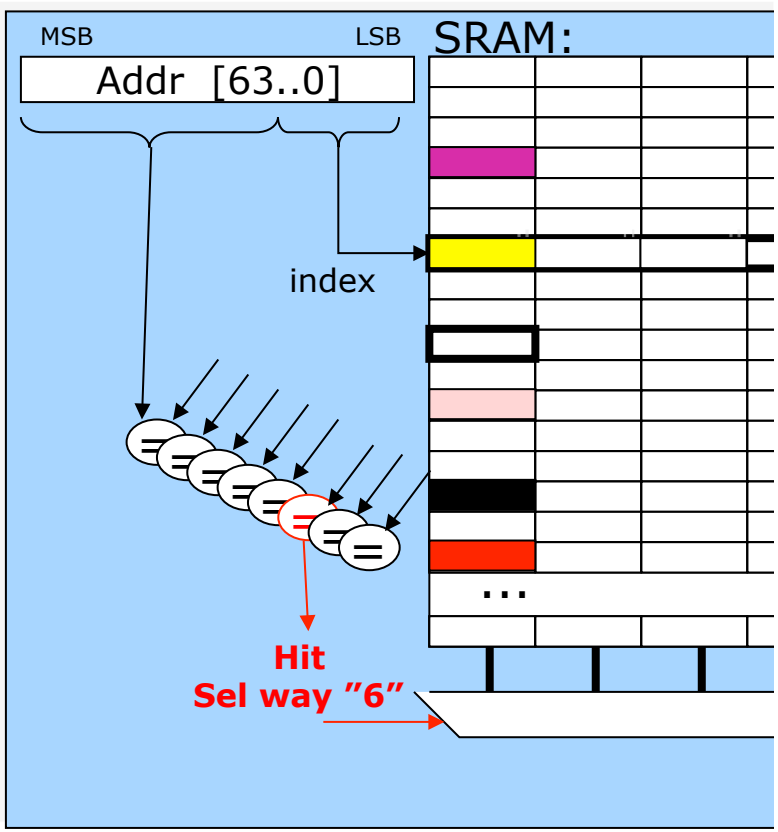


Padding of data structures



allocate more memory than needed

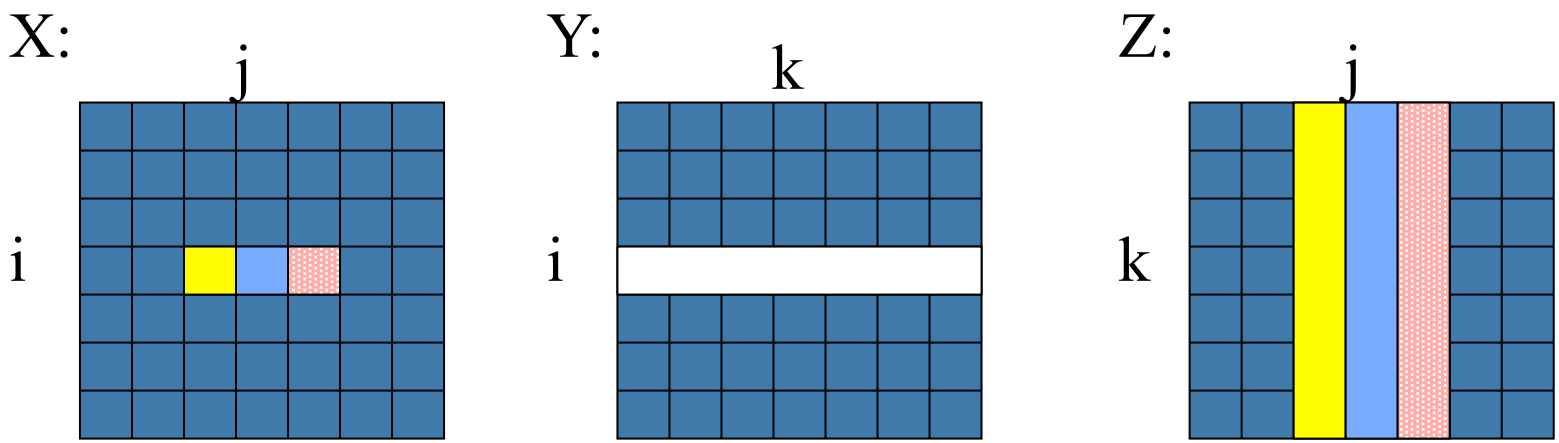
Generic Cache:



D

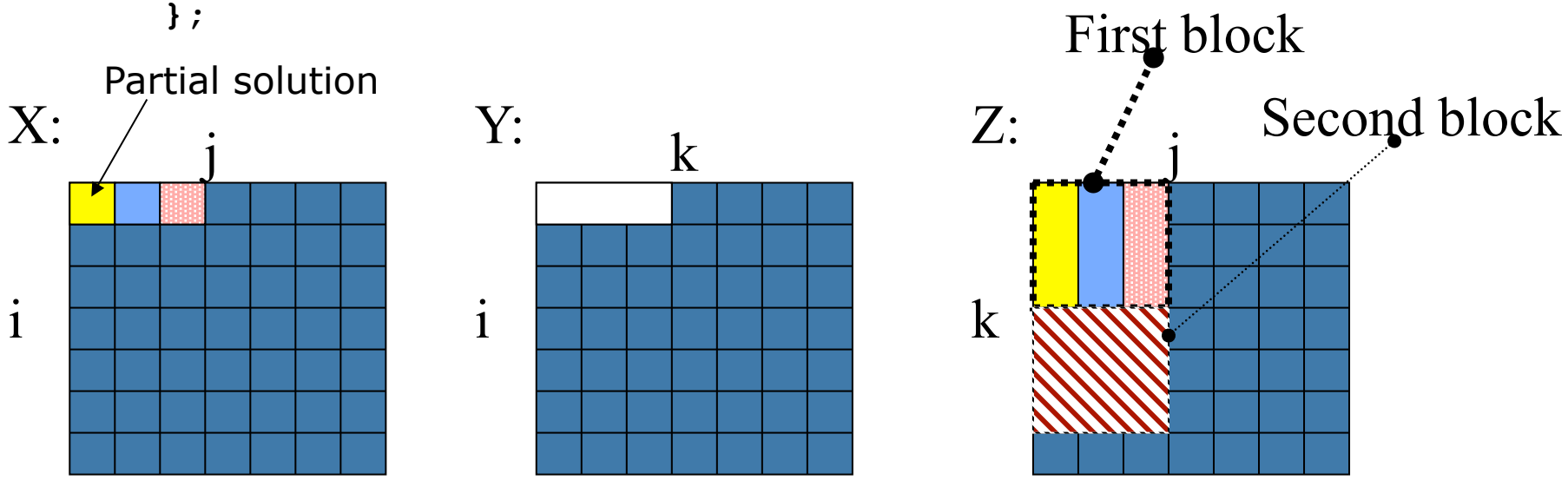
Blocking

```
/* Unoptimized  ARRAY: x = y * z */
for (i = 0; i < N; i = i + 1)
   for (j = 0; j < N; j = j + 1)
        {r = 0;
         for (k = 0; k < N; k = k + 1)
                r = r + y[i][k] * z[k][j];
         x[i][j] = r;
        };
```



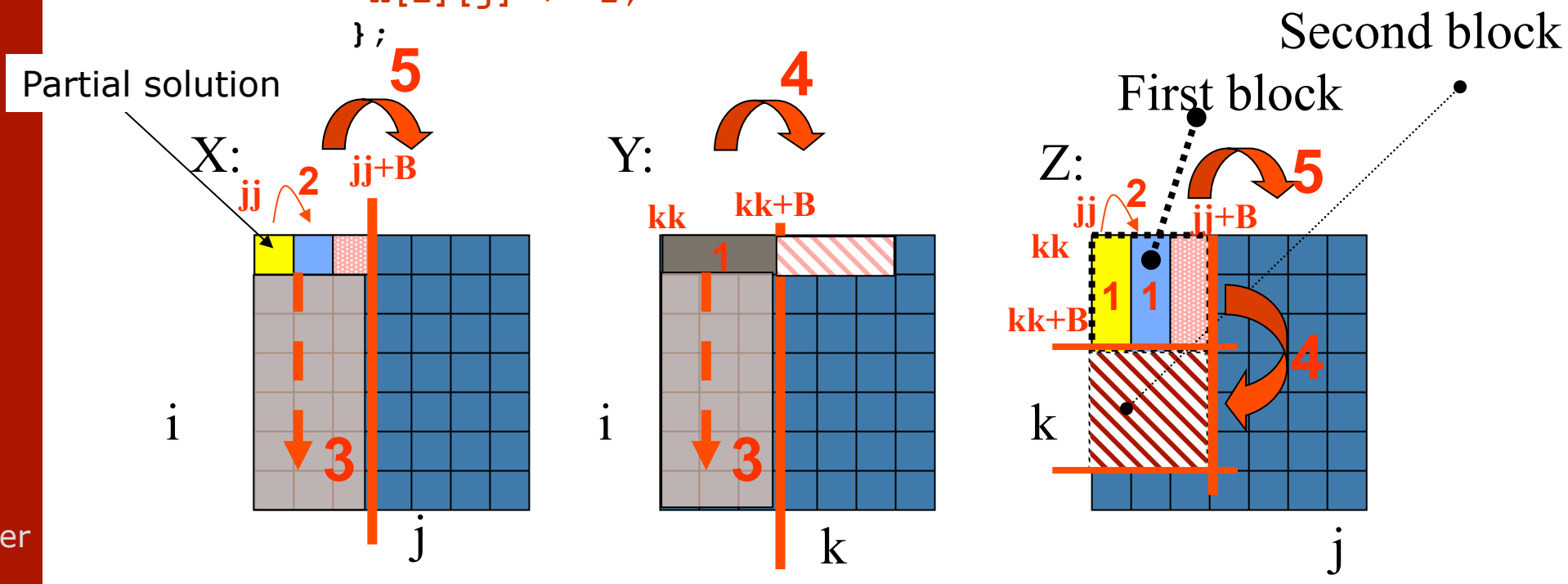
Blocking

```
/* Optimized  ARRAY: X = Y * Z */
for (jj = 0; jj < N; jj = jj + B)
for (kk = 0; kk < N; kk = kk + B)
for (i = 0; i < N; i = i + 1)
   for (j = jj; j < min(jj+B,N); j = j + 1)
        {r = 0;
         for (k = kk; k < min(kk+B,N); k = k + 1)
                r = r + y[i][k] * z[k][j];
         x[i][j] += r;
        };
```



Blocking: the Movie!

```
/* Optimized  ARRAY: X = Y * Z */
for (jj = 0; jj < N; jj = jj + B)                    /* Loop 5 */
for (kk = 0; kk < N; kk = kk + B)                    /* Loop 4 */
for (i = 0; i < N; i = i + 1)                        /* Loop 3 */
   for (j = jj; j < min(jj+B,N); j = j + 1)          /* Loop 2 */
        {r = 0;
         for (k = kk; k < min(kk+B,N); k = k + 1)    /* Loop 1 */
                r = r + y[i][k] * z[k][j];
         x[i][j] += r;
        };
```



Coherence traffic

ORIG:

Thread 0:

```
int a, total;
spawn_child()
for (int i; i< HUGE; i++) {
  /* do some work */
   a++;
 }
join()
total = a;
```

Child:

```
for (int i; i< HUGE; i++) {
   /* do some work*/
   a++;
}
```

OPT:

Thread 0:

```
int a, total;
spawn_child()
for (int i; i< HUGE; i++) {
   /* do some work */
   a++;
 }
join()
total += a;
```

Child:

```
int b;
for (int i; i< HUGE; i++) {
   /* do some work */
   b++;
 }
total += b;
```

False sharing

ORIG:

Thread 0:

```
int a, b;
spawn_child()
for (int i; i< HUGE; i++) {
  ...
   a++;
 }
join()
total = a + b;
```

Child:

```
for (int i; i< HUGE; i++) {
  ...
   b++;
}
```

OPT:

Thread 0:

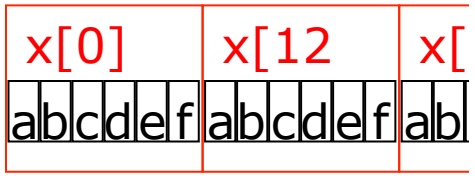
```
int a;
spawn_child()
for (int i; i< HUGE; i++) {
  ...
   a++;
 }
join()
total += a;
```

Child:

```
int b;
for (int i; i< HUGE; i++) {
  ...
   total += b;
}
```

Coherence Utilization

```
struct vec_type
{
        int a;
        int b;
        int c;
        int d;
        int e;
        int f;
};
```



ORIG:

Thread 0:

```
vec_type x[HUGE];
for (int i; i< HUGE; i++) {
  ...
   x[i].a++;
 }
spawn_child()
...
join()
```

Child (Thread 1)

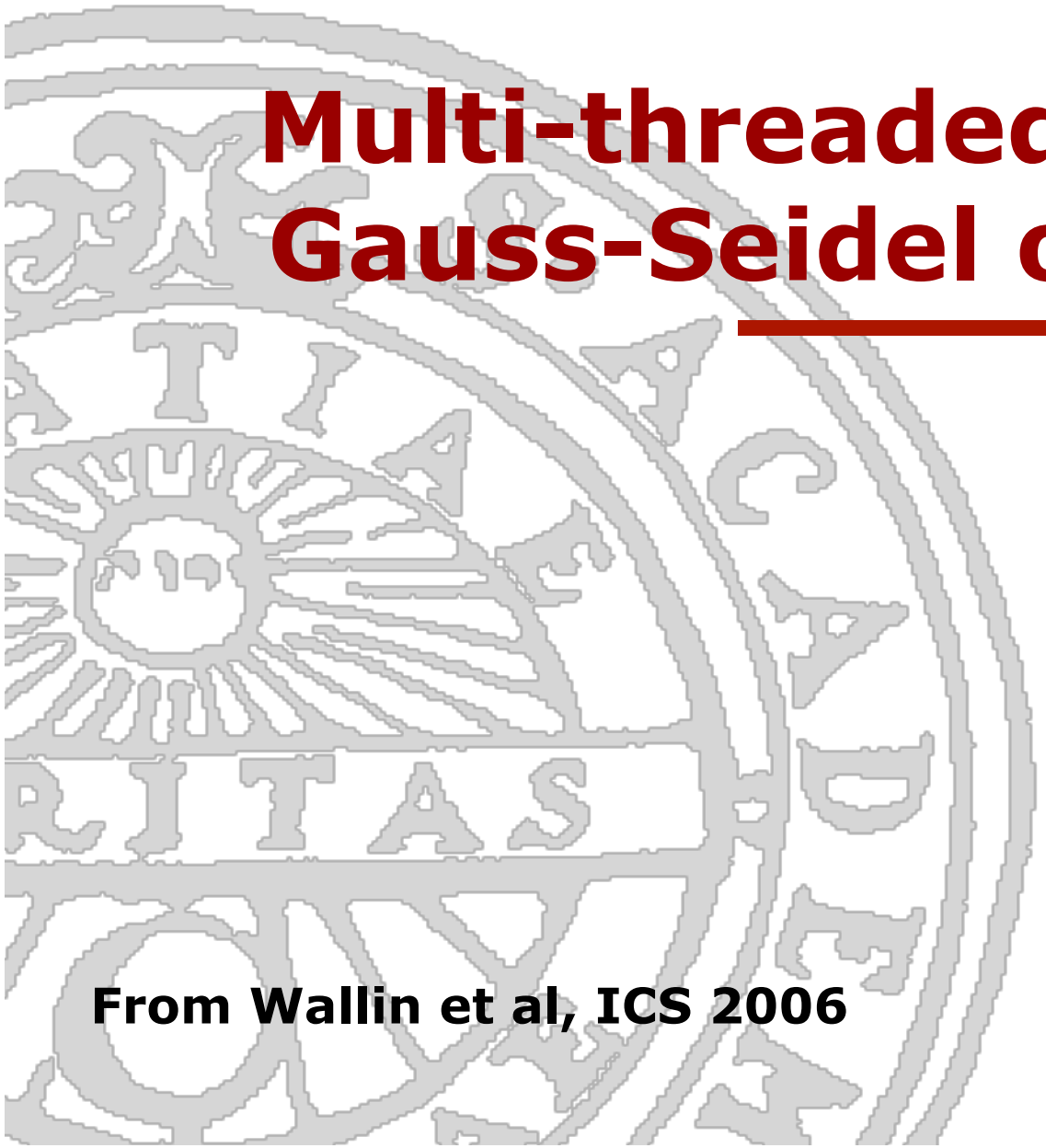
```
for (int i; i< HUGE; i++) {
   y[i] = x[i].a;
}
```

UPPSALA UNIVERSITET

UPMARC Uppsala Programming for Multicore Architectures Research Center

- Uppsala Programming for Multicore Architecture Center
- 62 MSEK grant / 10 years [$9M/10y]
  + related additional grants at UU = 130MSEK
- Research areas:

Erik:
  - Performance modeling
  - New parallel algorithms
  - Scheduling of threads and resources
  - Testing & verification
  - Language technology
  - MC in wireless and sensors



Multi-threaded Case Study: Gauss-Seidel on Multicores

From Wallin et al, ICS 2006

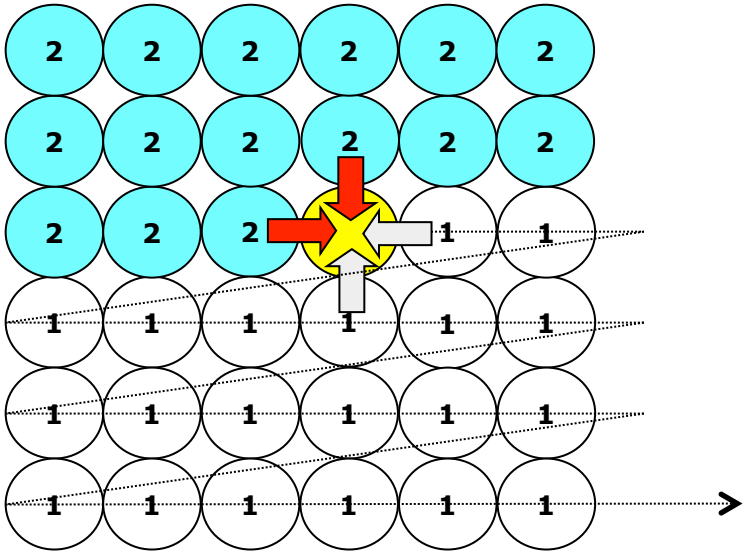
Criteria for HPC Algorithms

- Past:
  - Minimize communication
  - Maximize scalability (1000s of CPUs)
- Optimize for Multicore chip:
  - On-chip communication is "for free"
  - Scalability is limited to ~10 threads
  - The caches are tiny
  - Memory bandwidth is the bottleneck

➔ Data locality is key!

Example: Gauss Seidel

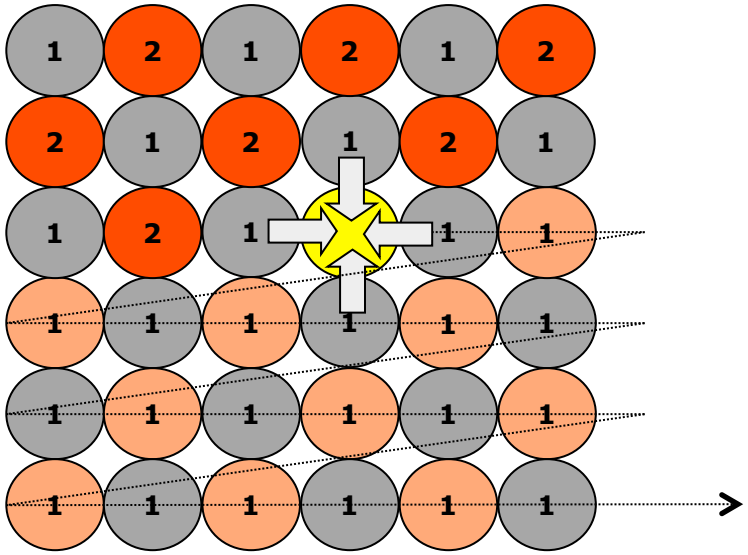
<u>Mission:</u> "Maximize the parallelism and minimize the inter-thread communication"




```
LOOP:
  UPDATE ALL POINTS
  IF (convergence_test)
     <done>
```

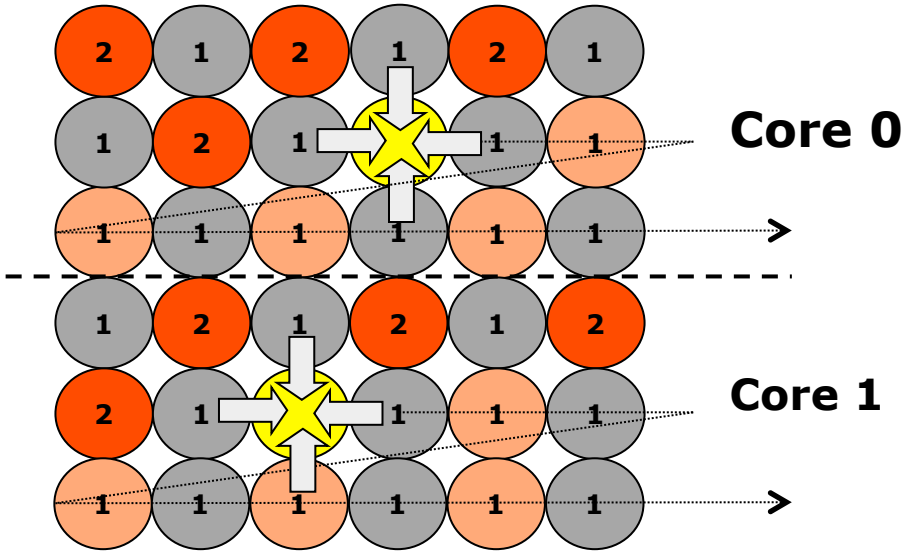
(Longer explanation: **<u>Finding a Door in the Memory Wall</u> @ HPCWire**)

State-of-the-art: Removing Dependence: Red/Black



LOOP:
  UPDATE ALL **RED** POINTS
  UPDATE ALL **BLACK** POINTS
  IF (convergence_test)
    <done>

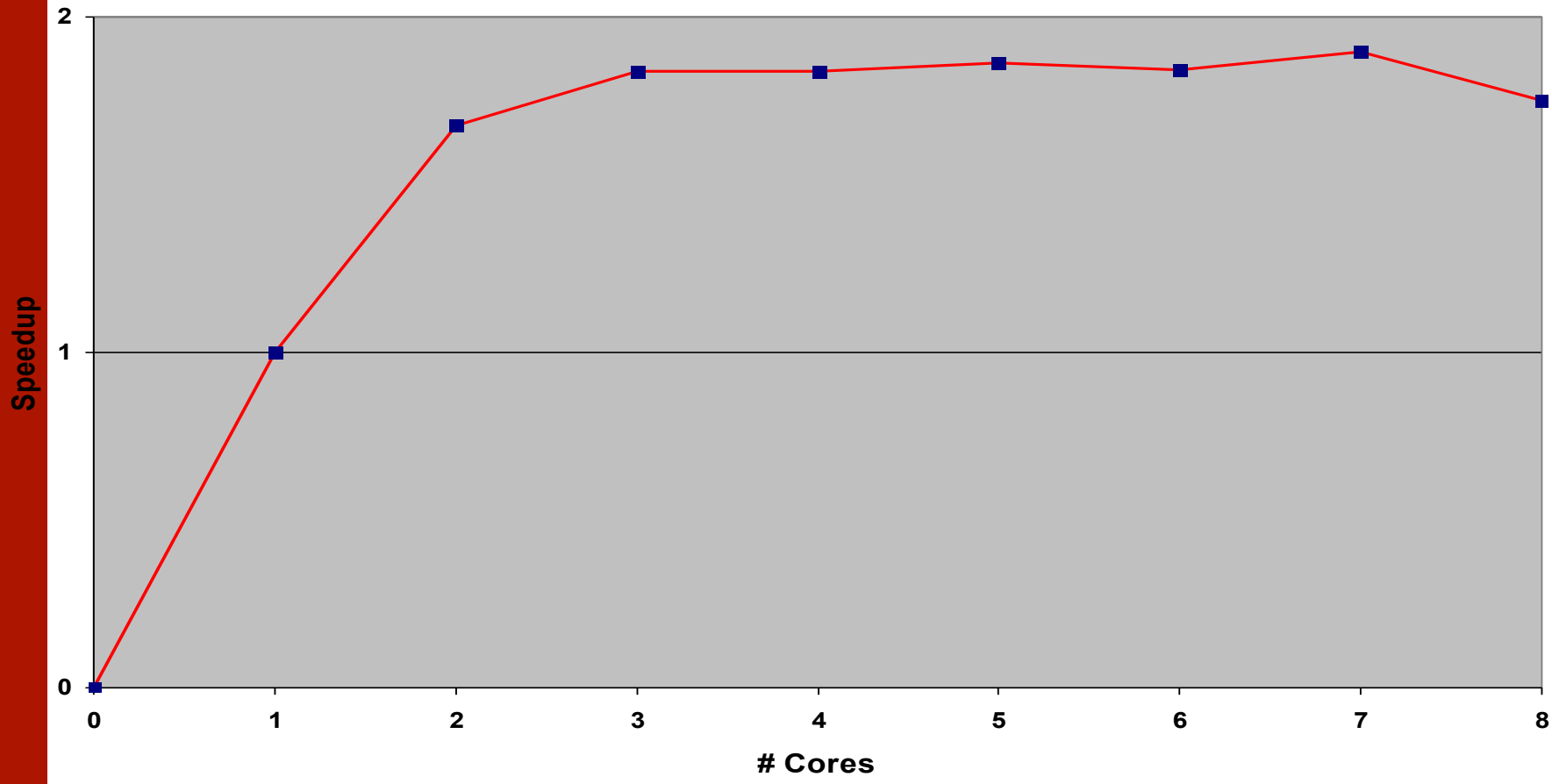
State-of-the-art: Red/Black, Parallelism = $N^2/2$



LOOP:
  IN PARALLEL: UPDATE ALL **RED** POINTS
  <barrier>
  IN PARALELL: UPDATE ALL **BLACK** POINTS
  <barrier>
  IF (convergence_test)
    <done>

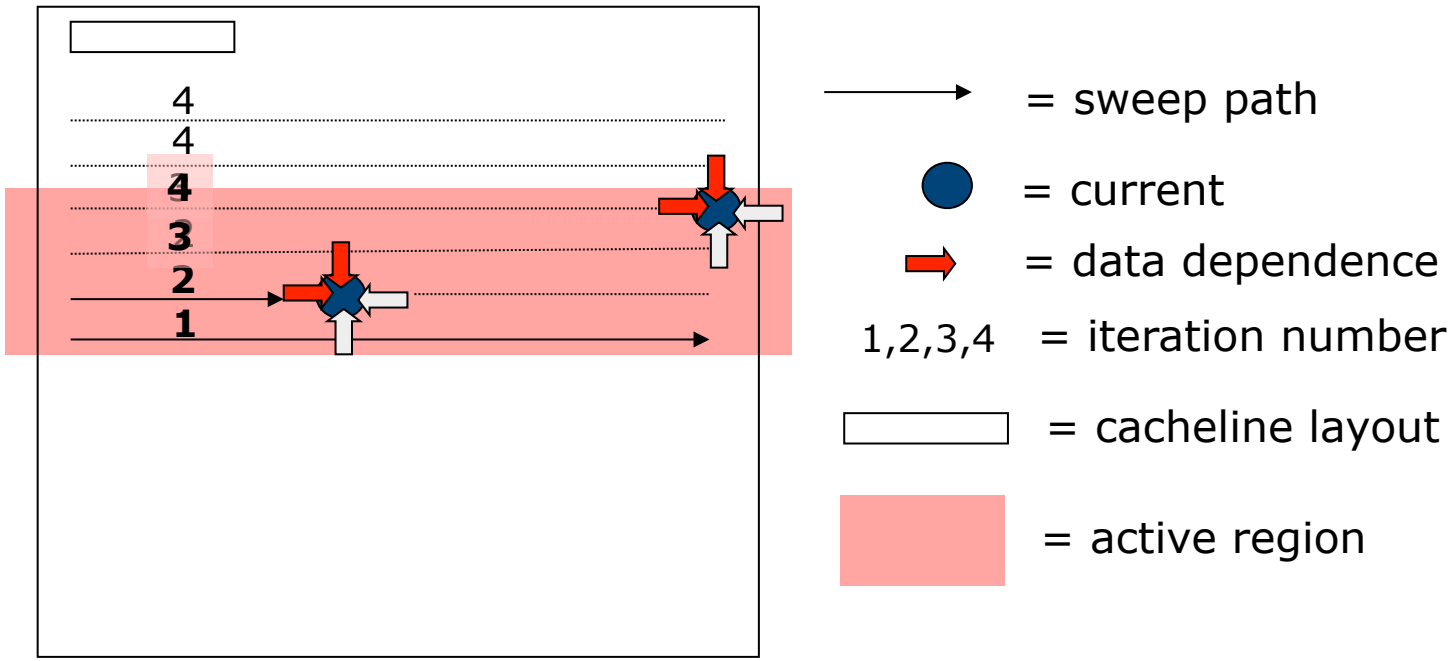
Limited communication ☺
$N^2/2$ parallelism ☺
Done!
Only one problem…

Only One Problem: Performance



Back to the drawing board: Temporal blocking for seq. code

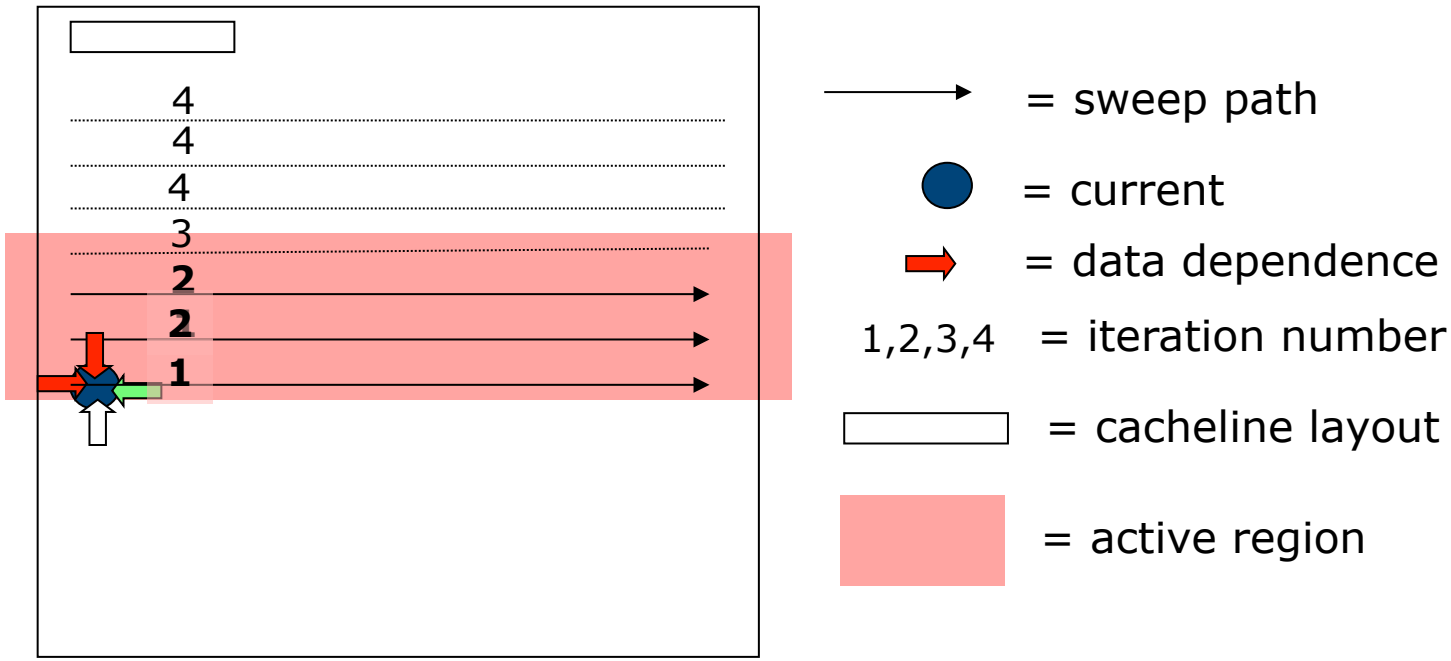
Communication is "for free" and moderate parallelism is OK
Priority 1: limit bandwidth needs!




```
LOOP:
   LOOP:
      UPDATE ALL POINTS IN ACTIVE REGION
      SLIDE DOWN THE REGION
   IF (convergence_test)
    <done>
```

Back to the drawing board: Temporal blocking for seq. code

Communication is "for free" and moderate parallelism is OK
Priority 1: limit bandwidth need!

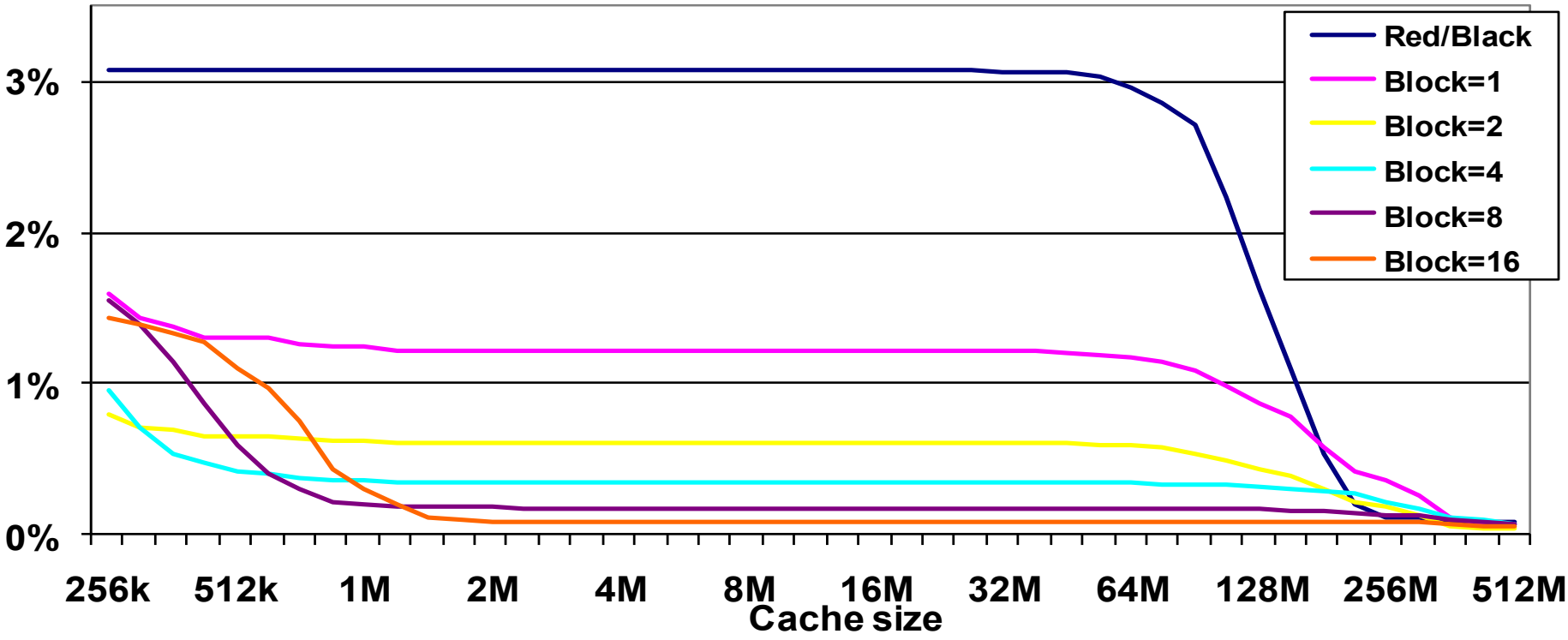



```
LOOP:
   LOOP:
      UPDATE ALL POINTS IN ACTIVE REGION
      SLIDE DOWN THE REGION
   IF (convergence_test)
    <done>
```

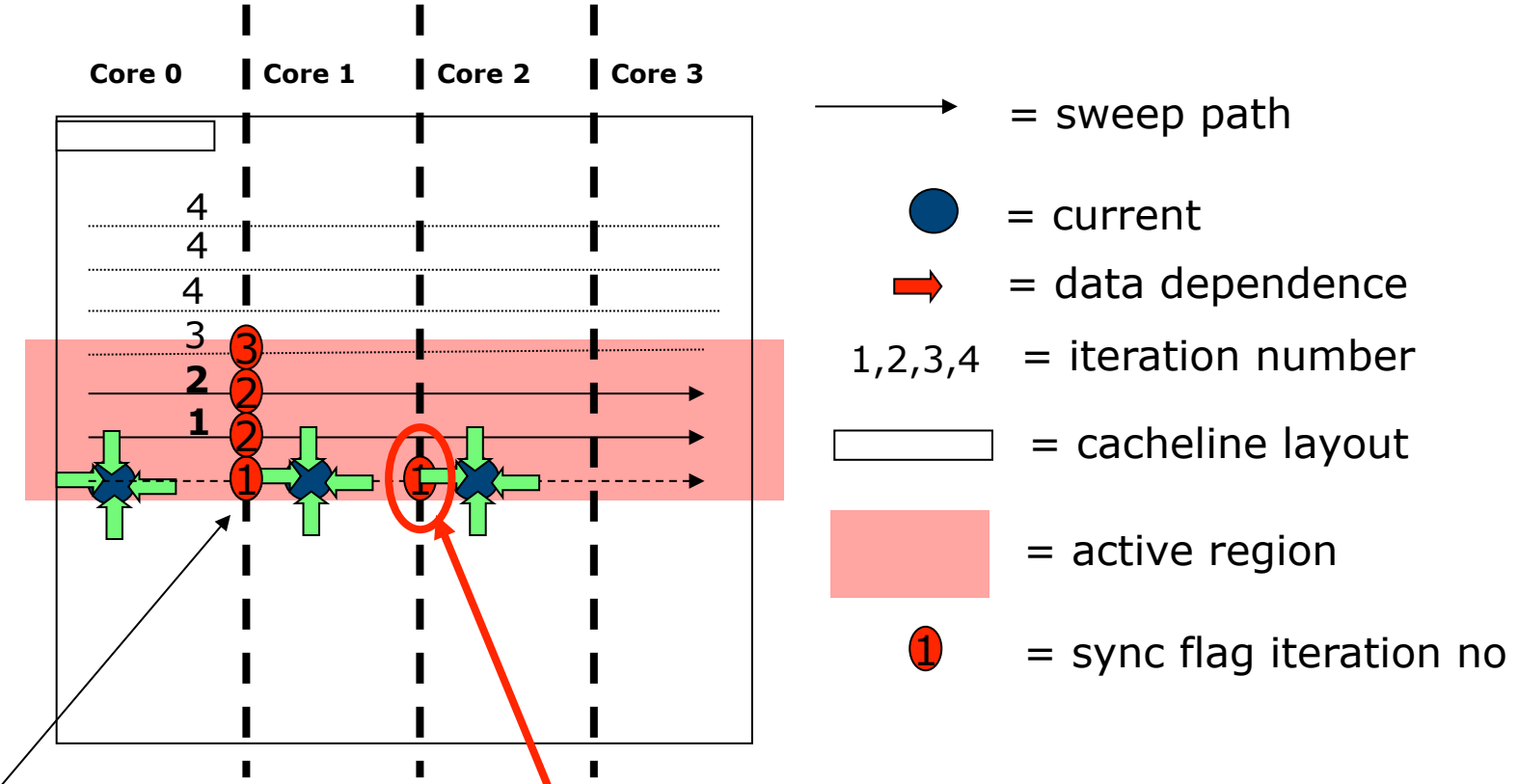
4 iterations in one sweep!

DRAM_traffic(cache_size)

Fetch Rate,
i.e, fraction of mem_ops generating DRAM traffic



G-S, temp block Parallelism = N

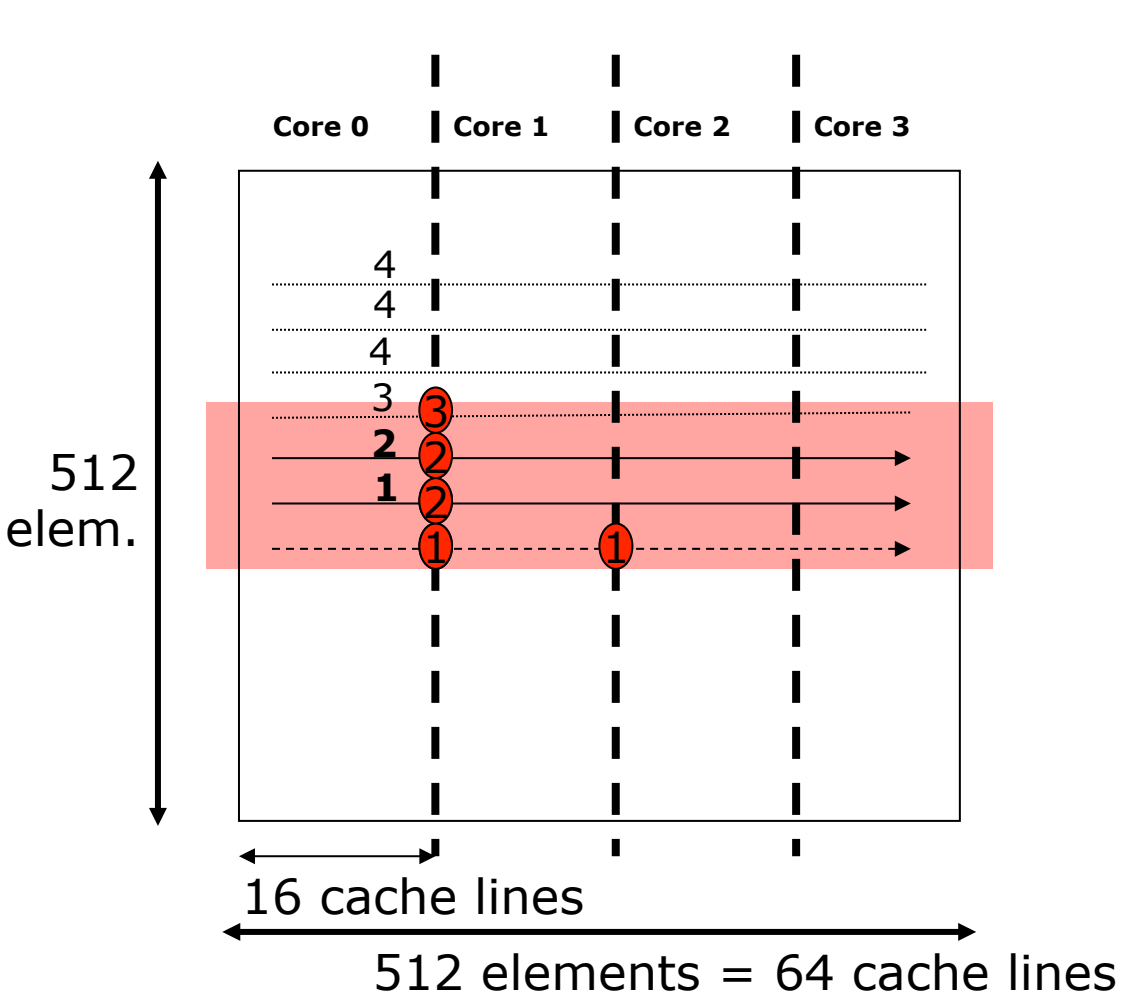


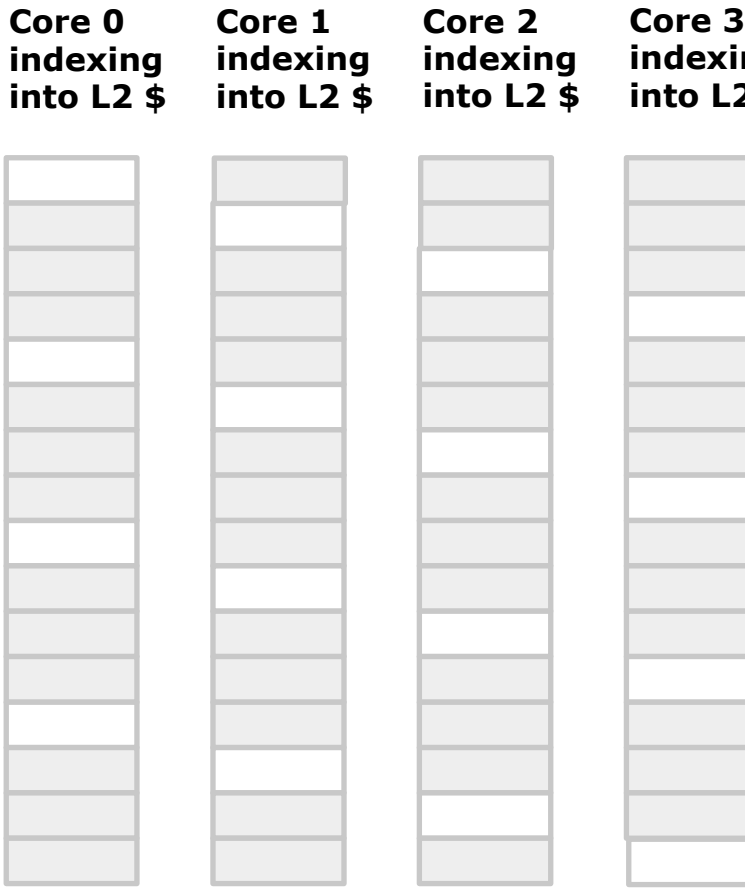
Synchronization flags

Wait until ”lefty” is done:
Lots of communication ☹
- Producer/Consumer Flag
- Sharing of data values

Only N-fold parallelism ☹

Problems we ran into 1 (2)

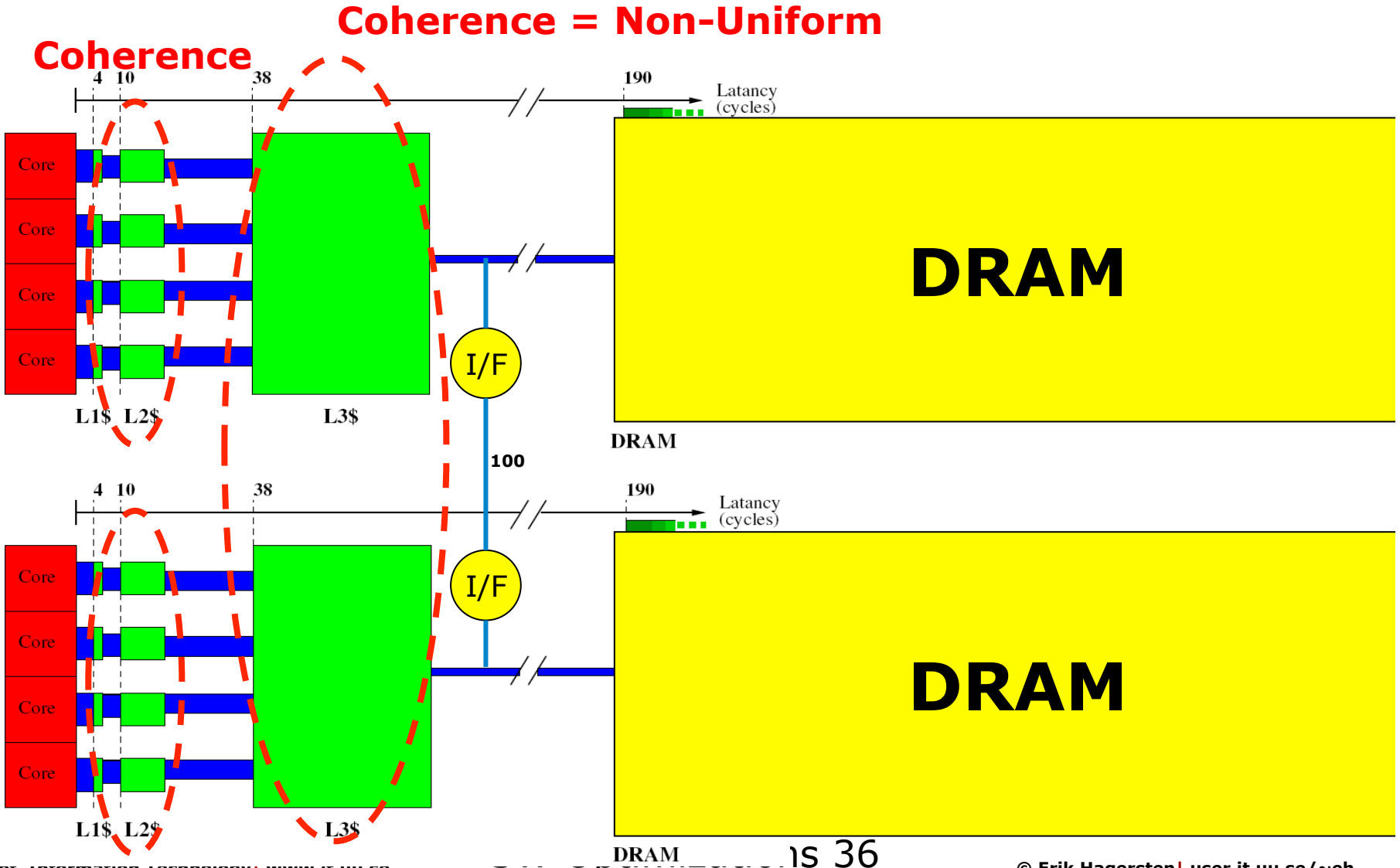




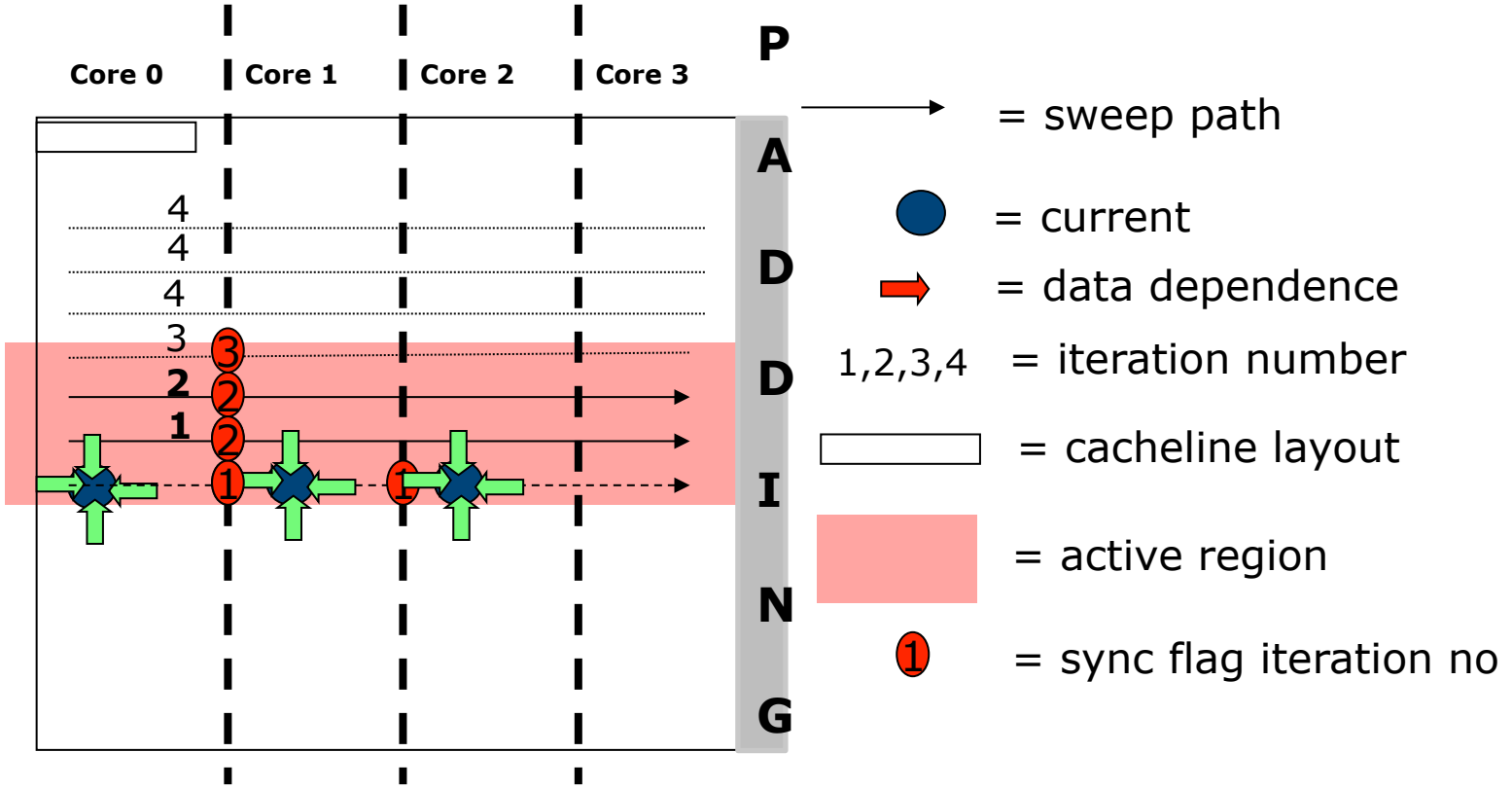
Problems we ran into 2 (2)

- We had a loop nesting problem that the compiler optimized away
- … sometimes

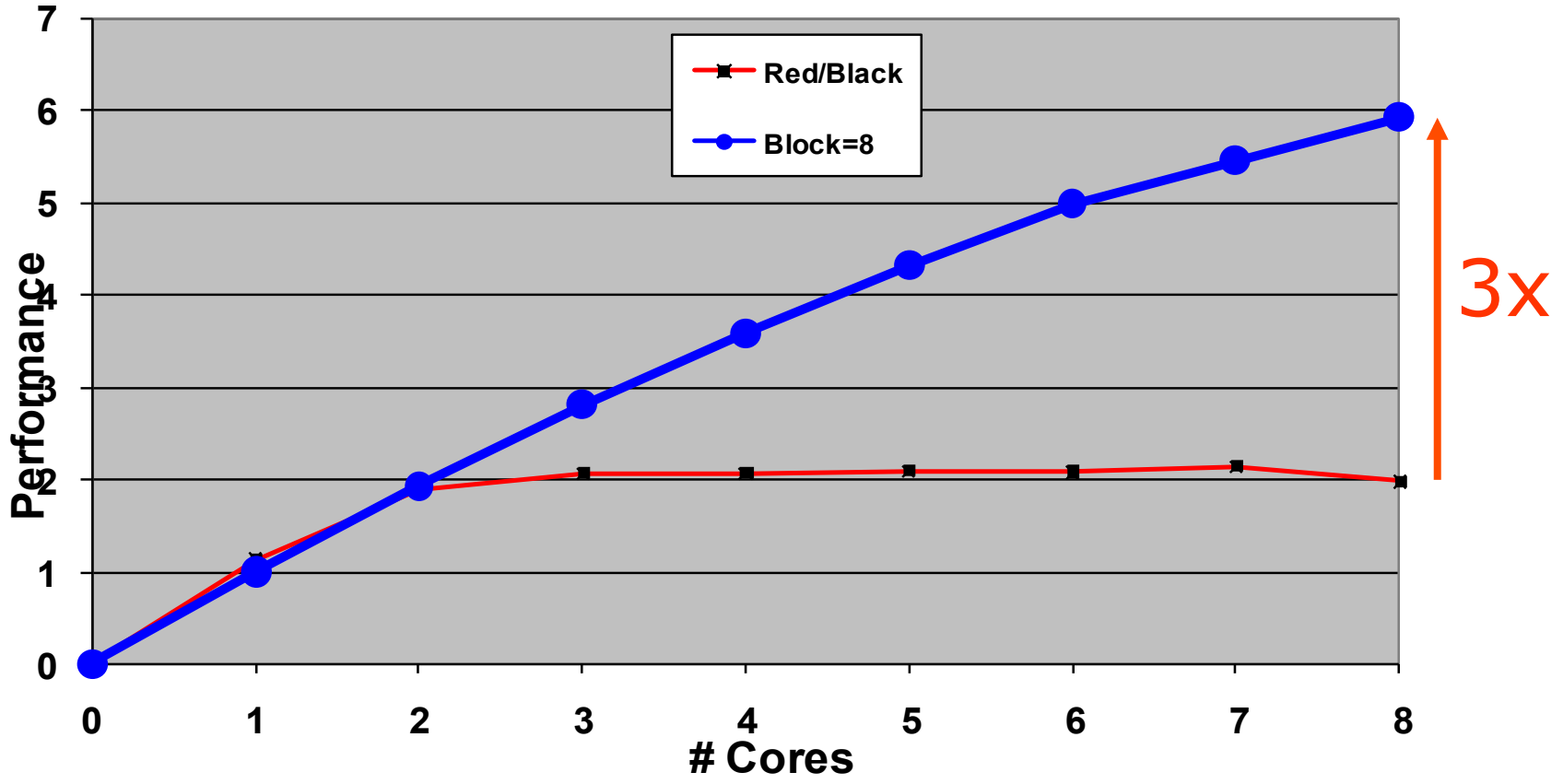
Running on a Multisocket



Example: G-S, temp blocking



Lessons Learned: Optimize cache usage BEFORE parallelizing



[Wallin, Löf, Holmgren, Hagersten @ ICS 2006]