Shared Memory Programming: pThreads and OpenMP

IBM

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Agenda

- Shared Memory
  - Computer Architecture
  - Programming Paradigm
- pThreads
- OpenMP Compilers
  - Implementation
  - Compiler Internals
- Automatic Parallelization
- Work Distribution
- Performance
- Problems and Concerns

Compiling and Running an OpenMP Program

```
xlf90_r –O3 –qsmp –c openmp_prog.c
xlf90_r –qsmp –o a.out openmp_prog.o
export OMP_NUM_THREADS=4
./a.out &
ps –m –o THREAD
```

_r = reentrant code
Use –qsmp both for compiling and for linking

Shared Memory Programming

pThreads

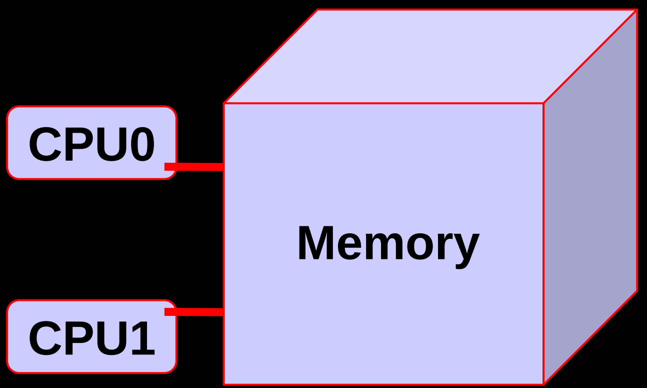
- POSIX standard
- Library functions
- Explicit fork and join
- Explicit synchronization
- Explicit locks
- Often used in "operational" environment
- Often used for M:N applications = many short tasks for a few processors

OpenMP

- Industry Standard
- Compiler assist:
  - Directives (Fortran)
  - Pragmas (C, C++)
- Explicit "fork" and "join"
- Implicit synchronization
- Implicit locks
- Often used in data analysis
- Often used for 1:1 applications = one task per processor

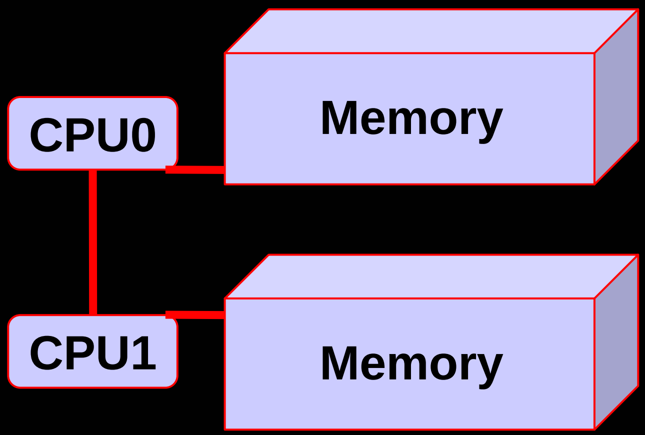
Shared Memory Architecture

- One address space
  - Multiple processor access
- Software synchronization
- Hardware (and software) cache coherence



Shared Memory Architecture Variation: NUMA

- Single address space
- Non-uniform memory latency
- Non-uniform memory bandwidth



Shared Memory Definition: Single address space

pThreads

- Standard for shared memory programming
- POSIX standard
- ALL modern computers
- Reentrant code:
  - Does not hold static data over successive call.
  - Important for f77 (static storage) programs

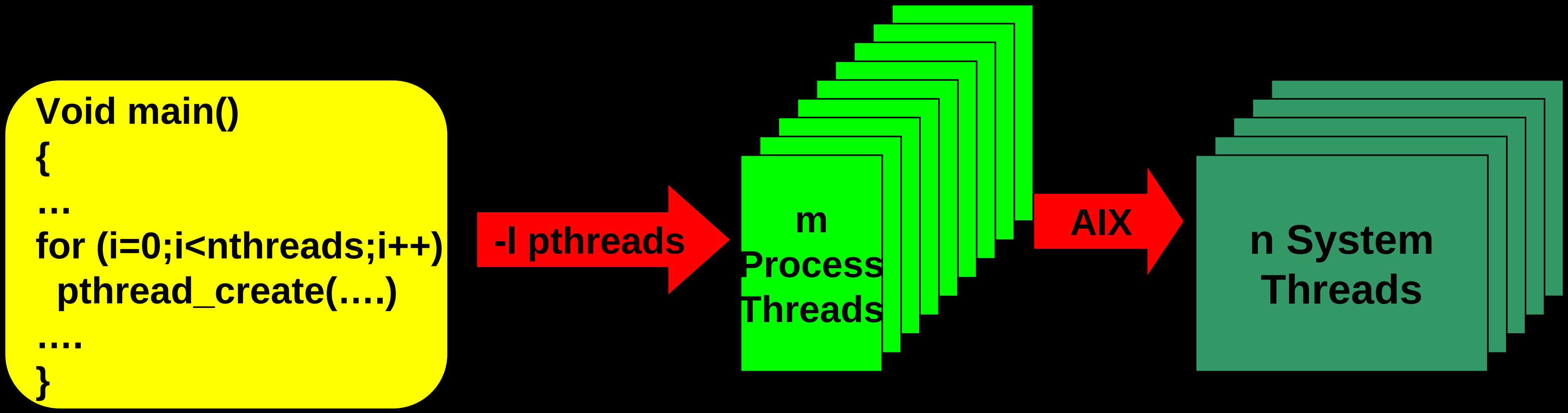
pThreads Thread Scope

- AIXTHREAD_SCOPE={S|P}
  - S: Thread is bound to a kernel thread
    - Scheduled by the kernel.
  - P: Thread is subject to the user scheduler
    - Does not have a dedicated kernel thread
    - Sleeps in user mode
    - Placed on the user run queue when waiting for a processor
    - Subjected to time slicing by the user scheduler
    - Priority of thread is controlled by user

pThreads Thread Scope

- Typically, user is concerned with process threads
- Typically, operating system uses system threads
  - Process to system thread mapping (pThreads default):
    - 8 to 1
      - –8 process threads map onto 1 system thread
- User can choose system or process threads
  - pthread_attr_setscope(&attr,PTHREAD_SCOPE_SYSTEM);
  - export AIXTHREAD_SCOPE=S
  - export AIXTHREAD_MNRATIO=m:n

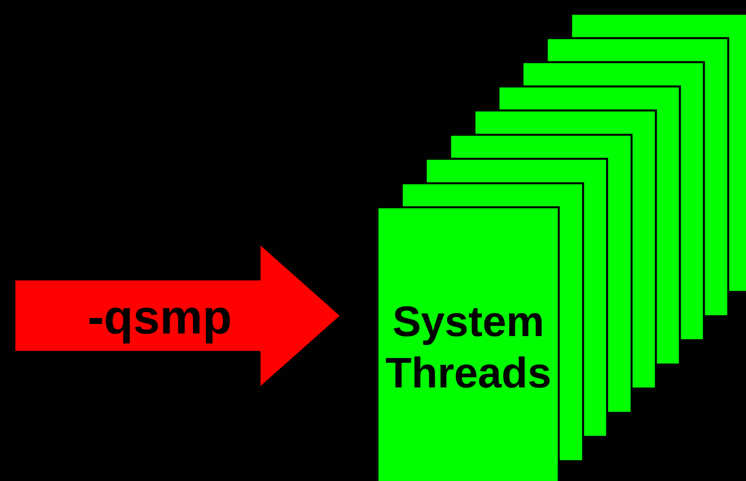
m:n Thread Scope



OpenMP Thread Scope

- 1:1 model
- Each user (process) thread is mapped to one system thread

```
Void main()
{
…
#pragma OMP parallel
for (i=0;i<nthreads;i++)
  work();
….
}
```



OpenMP and pThreads

- OpenMP uses a shared memory model similar to pThreads
  - Fork
  - Join
  - Barriers (mutexes)
- NOT strictly built on top of pThreads

OpenMP and pThreads

```
Void sub(n,A,B)
{

      #pragma omp parallel
      {
      #pragma omp for
            for (i=0;i<n;i++)
                  {
                    A[i] = func(B);
                  …
                  }
      }
            ....
}
```

```
//"Master" thread forks slave threa

main()
{
...
for (i = 0; i < num_threads; i++)
     pthread_create ( &tid[i],...
for (i = 0; i < num_threads; i++)
     pthread_join( &tid[i],  … );

}

void do_work(void *it_num)
 {for (i=start;i<ending;i++)
             A[i]=func(B);
    return ;
}
```

OpenMP Example

Fork

Locks

Locks

Join

```
Void  user_sub()
{
...
#pragma  omp parallel
{
...
#pragma omp for
    for (i=0;i<;i++
          {A[i] = ....
           B[i] = ..
          }
...
}

Return (0)
}
```

Parallel Regions and Work Sharing

```
Void  user_sub()
{
...
#pragma  omp parallel
{
…
#pragma omp for
 for (i=0;i<;i++){
      A[i] = ....
      B[i] = ….
     }
…
}

Return (0)
}
```

- **Parallel Region**
  - Master thread forks slave threads
  - Slave threads enter "re-entrant" code

- **Work Sharing**
  - Slave threads collective divide work
  - Various scheduling schemes
    - User choice

Parallelization Example

```
Void sub(n,A,B)
{

     #pragma omp parallel
     {
     #pragma omp for
          for (i=0;i<n;i++)
                 A[i] = func(B);
     }
          ....
}
```

Parallelization Example

```
void sub(n,A,B)
{
…
  #pragma omp parallel
    sub1(A,B);
...
}
```

Threads

```
void sub1(A,B)
{
…
#pragma omp for
            sub2(ns,ne,A,B)
            ....
}
```

```
void sub2(ns,ne,A,B)
{  for (i=ns;i<ne;i++)
    A[i] = func(B[i]))
}
```

OpenMP Work Distribution

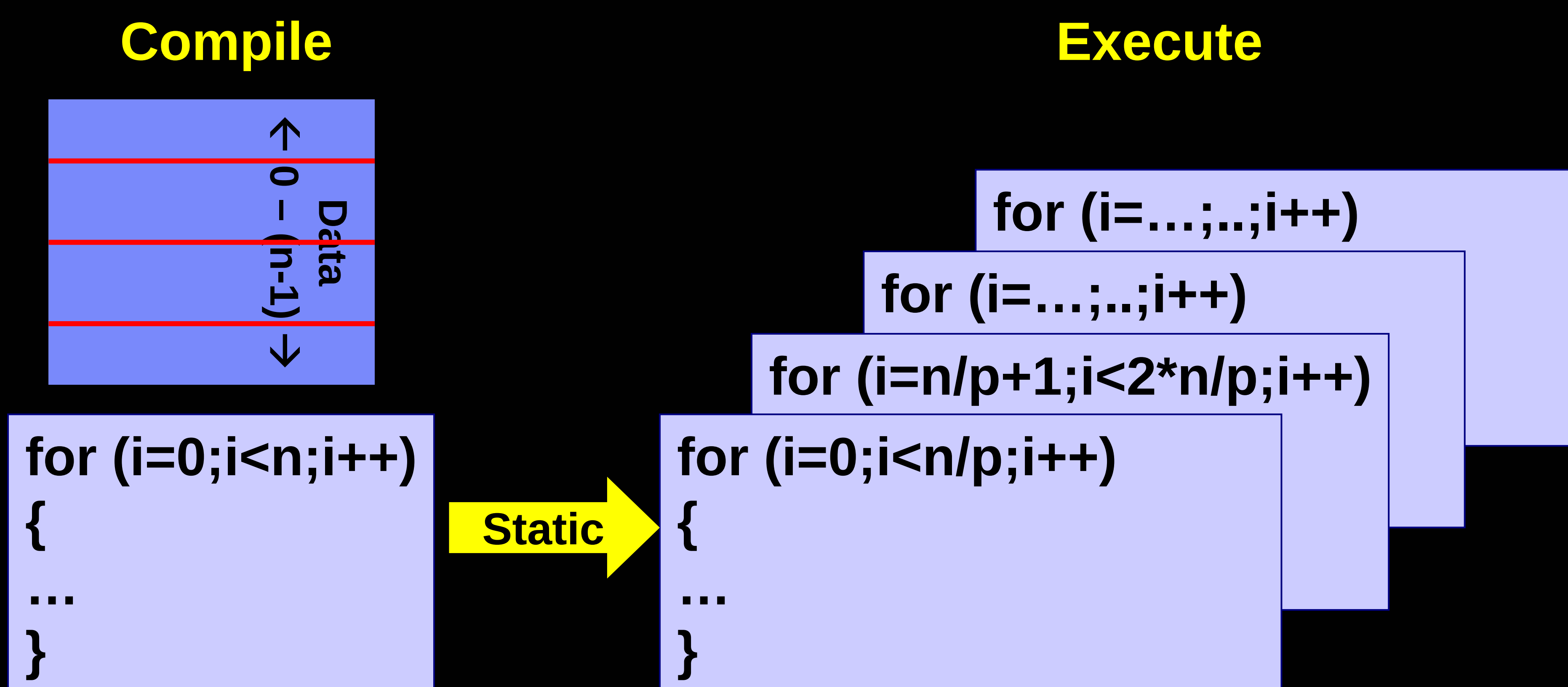
- Scheduling determined by the user
  - Directives
  - Environment variables
- STATIC: small overhead
  - Distribution done at compile time
- DYNAMIC: better for load balancing
  - Distribution done during execution
- GUIDED

Scheduling

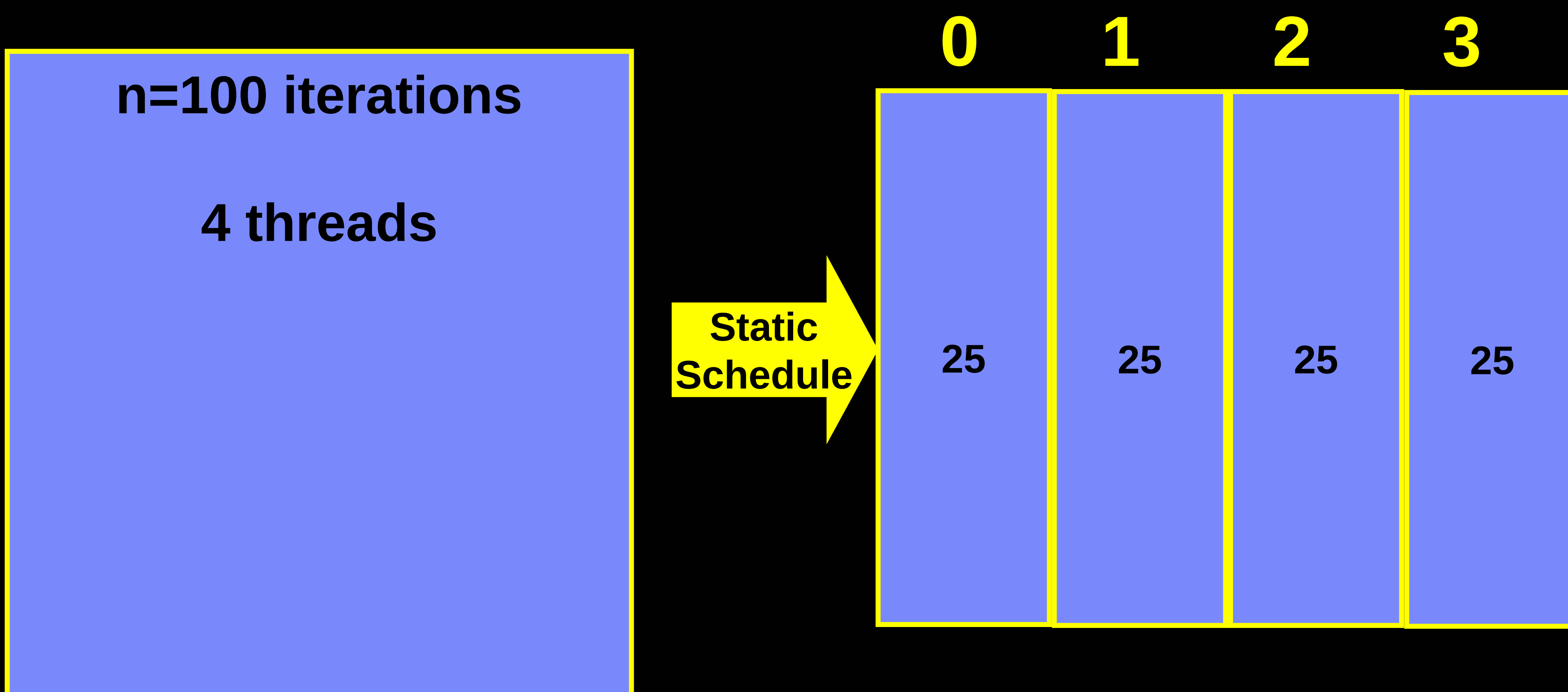
- Environment variable:
  - OMP_SCHEDULE={static, dynamic, guided}
- Pragma:
  - #pragma omp for schedule({static, dynamic, guided})
- Full syntax:
  - OMP_SCHEDULE={s…,d…,g…}[(chunk_size)]
  - #pragma … schedule({s…,d…,g…},[chunk_size])

Scheduling: Static

- Default (xlf and xlc)
- Number of iterations per thread determined before loop execution



Static Scheduling Example



Scheduling: Dynamic

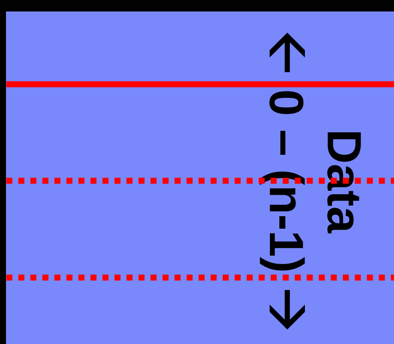
- **Next thread takes next slab**

Execute

Next available thread takes next available slab

Next thread takes size n/p slab

Compile

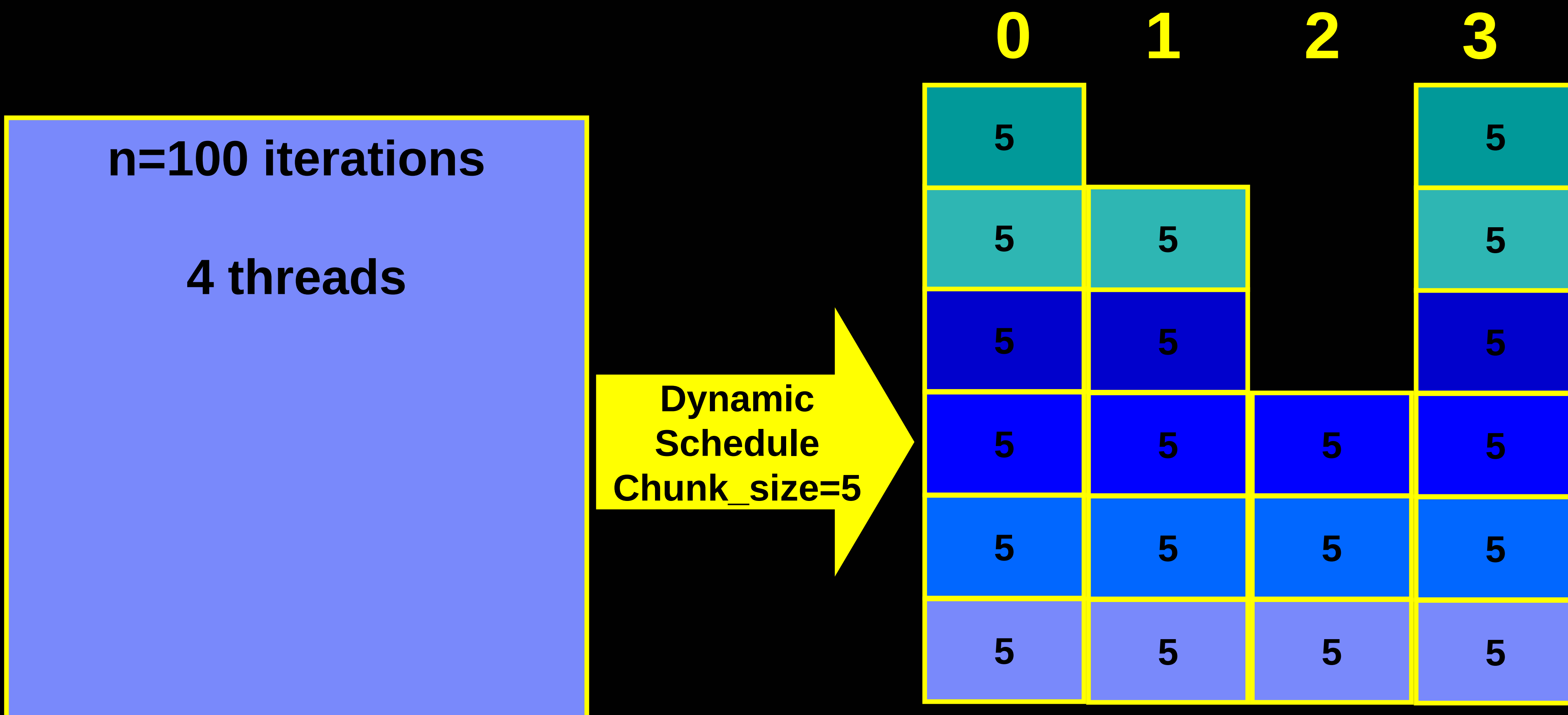



```
for (i=0;i<n;i++)
{
...
}
```

Dynamic

```
for (i=0;i<n/p;i++)
{
...
}
```

Dynamic Scheduling Example



Scheduling: Guided

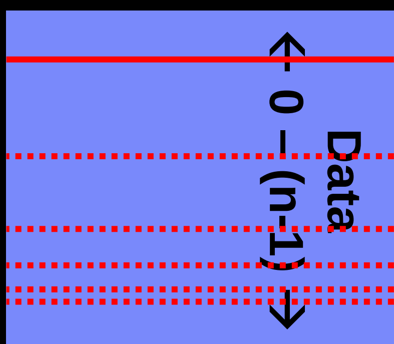
- **Next thread takes reduced size slab**

Execute

Next available thread takes next further reduced slab

Next thread takes size (n-(n/p)/p slab

Compile

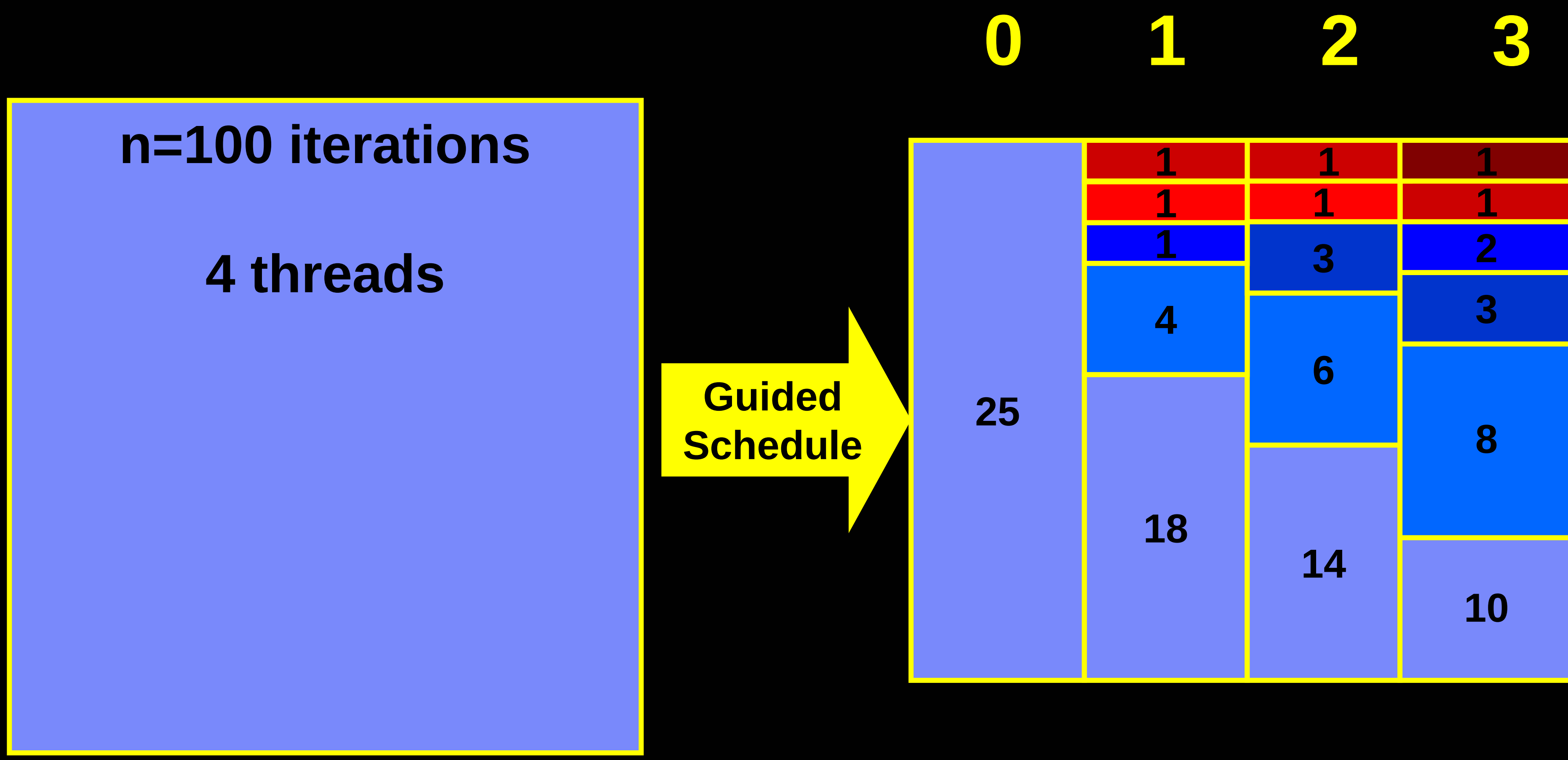



```
for (i=0;i<n;i++)
{
…
}
```

Guided →

```
for (i=0;i<n/p;i++)
{
…
}
```

Guided Scheduling Example



Performance Concerns

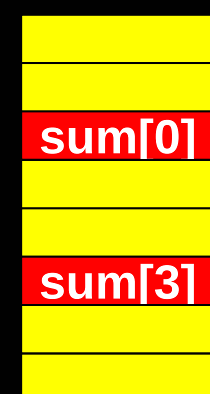
- False Sharing
  - Cache coherency thrashing
- Load balance
  - Uneven number distribution
  - Uneven work units
  - Triangles
- Barriers
  - Synchronization is expensive

False Sharing

- Multiple processors (threads) write to same cache line
  - Valid shared memory operation but causes severe performance penalty
  - Common in older Cray parallel/vector codes
- Dangerous programming practice
  - Difficult to detect

```
float sum[8];
#pragma omp parallel
p = ...my thread number...
#pragma omp for
for (i=1;i<n;i++)
  sum[p] = sum[p] + func(i,n);
```

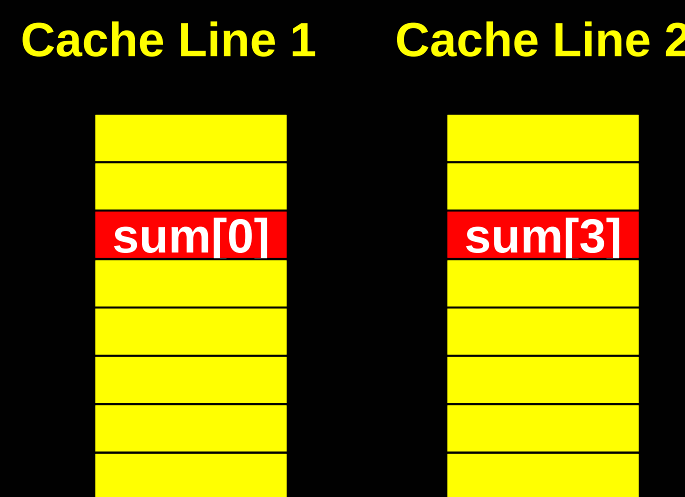
Cache Line



Corrected False Sharing

- Each processor (thread) writes to own cache line
  - Wastes a tiny bit of memory
  - Cache line is 128 bytes = thirty-two 4-byte words

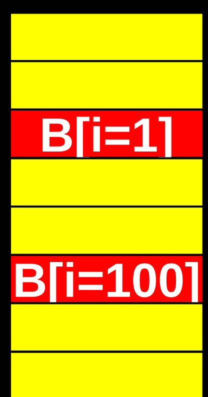
```
float sum[8*32];
#pragma omp parallel
p = ...my thread number...
#pragma omp for
for (i=1;i<n;i++)
   sum[p*32] = sum[p*32] + func(i,n);
```



False Sharing

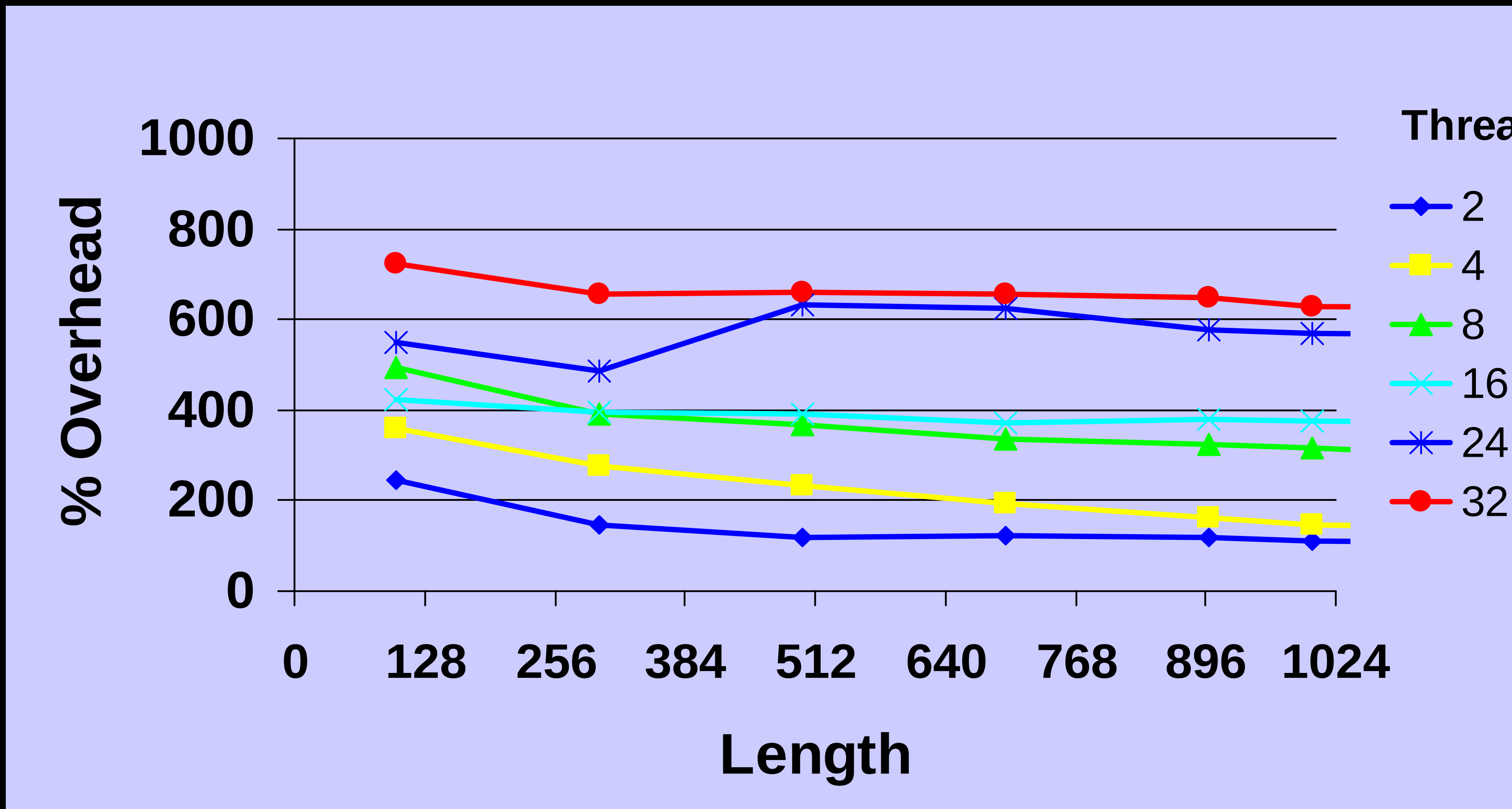
- Multiple threads accessing SAME line cause contention

Cache Line

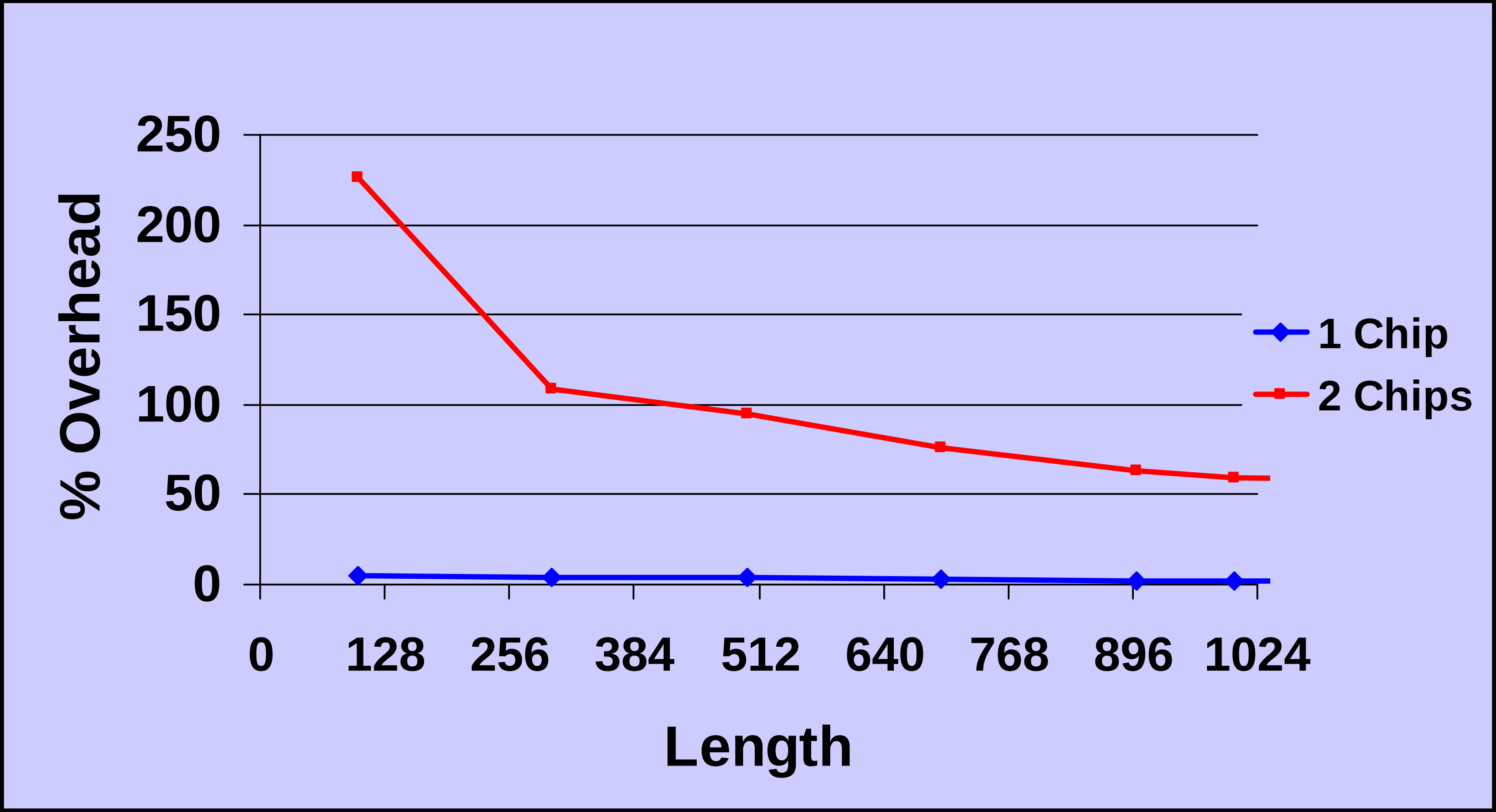



```
#pragma omp for
for (i=1;i<n;i++) {
   k = index[i];
   A[i] = B[k] + i;
```

Effect of False Sharing

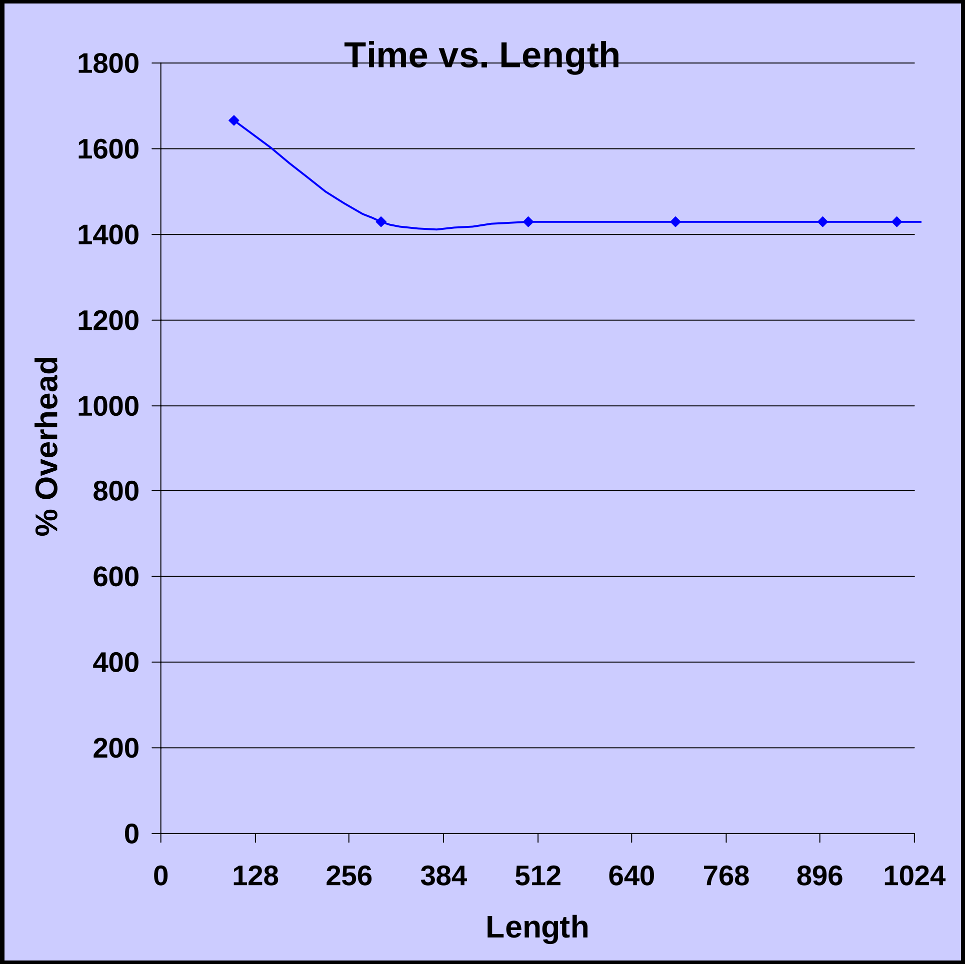


Effect of False Sharing: Two threads on Same Chip



False Sharing Summary

- Effect is worse with smaller features
- Effect is worse with more threads



Summary

- Shared memory programming
  - Only works on single address space node
- Dynamic constructs
  - Good for load balancing
- Concerns:
  - False sharing
  - Critical regions