High Performance Application Optimization on CPUs

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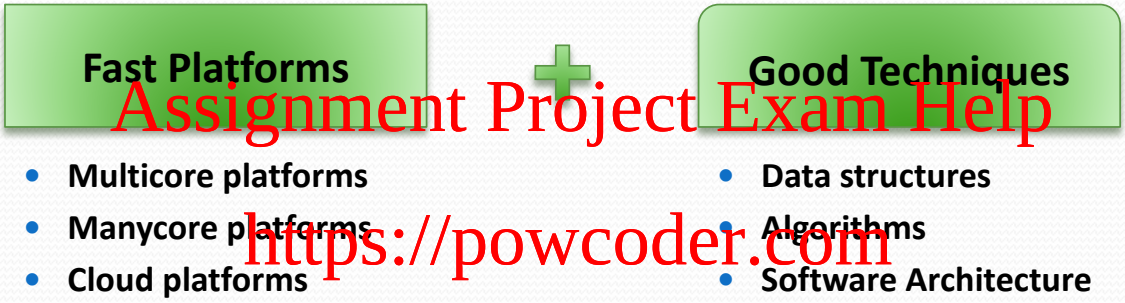
What we discussed last time:



- Highlighted the difference between multicore and manycore platforms
- Discussed the multicore and manycore platform intricacies

- **Exposing** concurrency in the k-means algorithm
- **Exploiting** parallelism by **exploring** mappings from application to platform

Example 7: Sequential Optimization

```
#include <omp.h>
#include <stdio.h>
static long num_steps = 100000000; double step;
#define NUM_THREADS 2
int main ()
{
     int i; double pi, x, local_sum; int nthreads;
     step = 1.0/(double) num_steps;
     #pragma omp parallel num_threads(NUM_THREADS) private(x, local_sum)
     {
          int i, id = omp_get_thread_num(); local_sum=0.0;
          int nthrds = omp_get_num_threads();
          double hoop = nthrds*step;
          for (i=id, x=(i+0.5)*step;i< num_steps; i=i+nthrds) {
            x += hoop;
            local_sum += 4.0/(1.0+x*x);
          }
          #pragma omp critical
          pi += local_sum * step;
     }
     printf("pi = %f \n", pi);
     return 0;
}
```

Sequential: 2.12 seconds

0.46 seconds

Outline

- Multicores Shared-Memory Platforms
- OpenMP – API for Shared-Memory Multiprocessing
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  - Example: numerical integration of Pi
  - Shared variable synchronization
  - **SPMD vs worksharing**
  - Data environment options
  - Advanced worksharing options
  - Synchronization options
- Sequential Optimizations
  - Cost Model
  - Cost Reduction

SPMD vs. Worksharing

- A parallel construct by itself creates an SPMD
  - "Single Program Multiple Data"
  - Programmer must explicitly specify what each thread must do differently
  - The division of work is hard-coded in the program
- Opportunity:
  - Many parallel regions are loops
- Question:
  - Can we make it easier to parallelize these loops?

OpenMP: Parallel For

- One of the worksharing constructs OpenMP provide is **"omp for"**

Sequential code

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

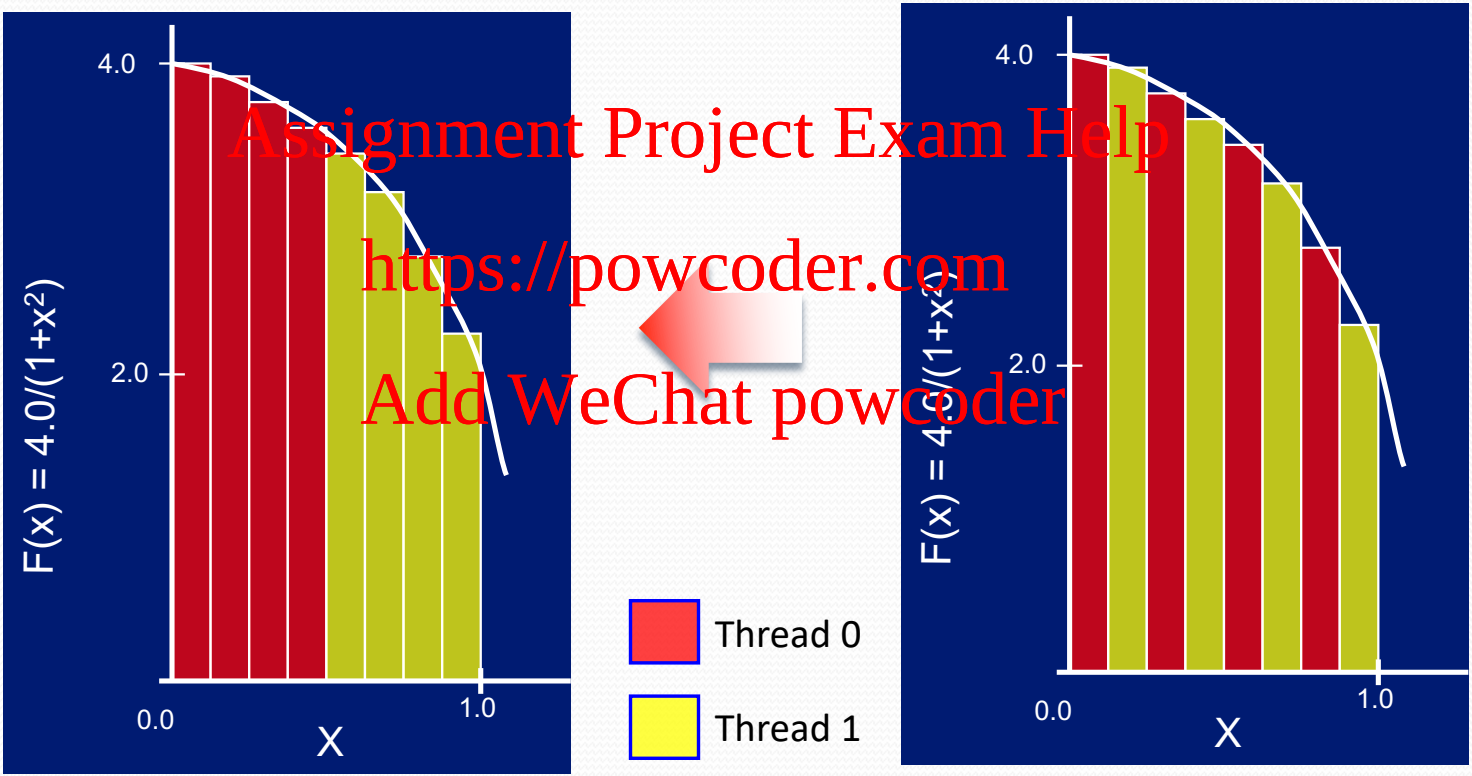

OpenMP **"parallel"** region

```
#pragma omp parallel
{
        int id, i, Nthrds, istart, iend;
        id = omp_get_thread_num();
        Nthrds = omp_get_num_threads();
        istart = id * N / Nthrds;
        iend = (id+1) * N / Nthrds;
        if (id == Nthrds-1)iend = N;
        for(i=istart;i<iend;i++)  { a[i] = a[i] + b[i];}
}
```

OpenMP **"parallel"** region and a worksharing **"for"** construct

```
#pragma omp parallel
#pragma omp for
        for(i=0;i<N;i++)  { a[i] = a[i] + b[i];}
```

Other Concurrency Opportunities



Example 8: Parallel For and Reduction

```
#include <omp.h>
#include <stdio.h>
static long num_steps = 100000000; double step;
#define NUM_THREADS 2
int main ()
{
     int i; double pi, x, sum = 0.0;
     step = 1.0/(double) num_steps;
     #pragma omp parallel private(x)
     {
          #pragma omp for reduction(+:sum)
          for (i=0;i< num_steps; i++){
               x = (i+0.5)*step;
               sum = sum + 4.0/(1.0+x*x);
          }
     }
     Pi = sum * step;
     printf("pi = %f \n", pi);
     return 0;
}
```

Sequential: 2.12 seconds

1.22 seconds

Reduction is more scalable than critical sections.

Loops must not have loop carry dependency. **Limitation of compiler technology.**

"i" is private by default

Combined Parallel/Worksharing Construct

- OpenMP shortcut: Put the "parallel" and the worksharing directive on the same line


```
double  res[MAX]; int i;
#pragma omp parallel
{
   #pragma omp for
   for (i=0;i< MAX; i++) {
       res[i] = huge();
   }
}
```


```
double  res[MAX];  int i;
#pragma omp parallel for
   for (i=0;i< MAX; i++) {
       res[i] = huge();
   }
```

OpenMP: Working With Loops

- Basic approach
  - Find compute intensive loops
  - Make the loop iterations independent . So they can safely execute in any order without loop-carried dependencies
  - Place the appropriate OpenMP directive and test


```
double hoop = nthrds*step;
for (i=id, x=(i+0.5)*step;i< num_steps; i=i+nthrds) {
  x += hoop;
  sum = sum + 4.0/(1.0+x*x);
}
```

x depend on i not in for

```
for (i=0;i< num_steps; i++){
     x = (i+0.5)*step;
     sum = sum + 4.0/(1.0+x*x);
}
```

OpenMP: Reductions

```
for (i=0;i< num_steps; i++){
    x = (i+0.5)*step;
    sum = sum + 4.0/(1.0+x*x);
}
```

```
#pragma omp for reduction(+:sum)
for (i=0;i< num_steps; i++){
    x = (i+0.5)*step;
    sum = sum + 4.0/(1.0+x*x);
}
```

reduction (op : list)

1. A local copy of each list variable is made and initialized depending on the "op" (e.g. 0 for "+")
2. Updates occur on the local copy
3. Local copies are reduced into a single value and combined with the original global value

- Accumulating values into a single variable (sum) creates true dependence between loop iterations that can't be trivially removed
- This is a very common situation … it is called a "reduction".
- Support for reduction operations is included in most parallel programming environments.

OpenMP: Reduction Operators

- Many different associative operands can be used with reduction:
- Initial values are the ones that make sense mathematically.

Operator	Initial value
+	0
*	1
-	0

Operator	Initial value
&	~0
|	0
^	0
&&	1
||	0

Example 8: Parallel For and Reduction

```
#include <omp.h>
#include <stdio.h>
static long num_steps = 100000000; double step;

int main ()
{
     int i; double pi, x, sum = 0.0;
     step = 1.0/(double) num_steps;
     #pragma omp parallel for private(x) reduction(+:sum)
     for (i=0;i< num_steps; i++){
          x = (i+0.5)*step;
          sum = sum + 4.0/(1.0+x*x);
     }
     Pi = sum * step;
     printf("pi = %f \n", pi);
     return 0;
}
```

Sequential: 2.12 seconds

1.22 seconds

Advantage: we created a parallel program without changing any code and by adding 2 simple lines of text!

Disadvantage:
1) Lot's of pitfalls if you don't understand system architecture
2) The basic result may not the fastest one can do

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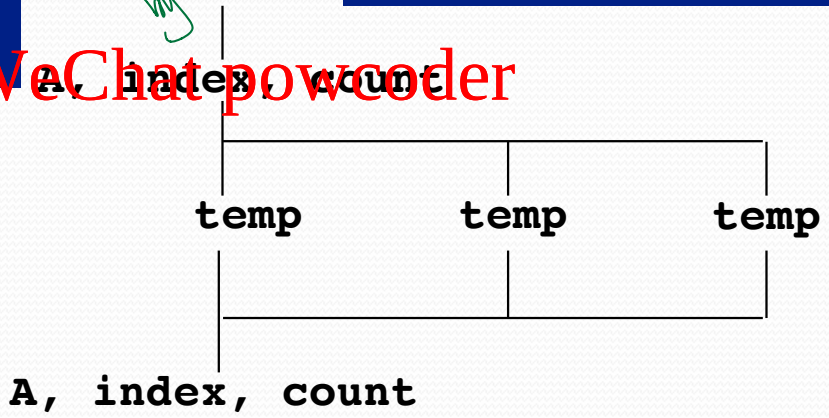
Data Environment in OpenMP

- Shared Memory programming model:
  - Most variables are shared by default
- Global variables are **SHARED** among threads
  - File scope variables, static
  - Dynamically allocated memory (ALLOCATE, malloc, new)
- But not everything is shared...
  - Functions called from parallel regions are **PRIVATE**
  - Automatic variables within a statement block are **PRIVATE**.

Example: Data Sharing

```
double A[10];
int main() {
    int index[10];
    #pragma omp parallel
        work(index);
    printf("%d\n", index[0]);
}
```

```
extern double A[10];
void work(int *index) {
  double temp[10];
  static int count;
  ...
}
```

A, index and count are shared by all threads.

temp is local to each thread

Changing Storage Attributes

- One can selectively change storage attributes for constructs using the following clauses:
  - SHARED
  - PRIVATE
  - FIRSTPRIVATE
- The final value of a private inside a parallel loop can be transmitted to the shared variable outside the loop with:
  - LASTPRIVATE

global before openMP, get value for each open
after open MP

typically use critical / atom(...

Example 9: firstprivate example

```
#include <omp.h>
#include <stdio.h>
static long num_steps = 100000000; double step;
#define NUM_THREADS 2
int main ()
{
     int i; double pi, x, local_sum = 0.0; int nthreads;
     step = 1.0/(double) num_steps;
     omp_set_num_threads(NUM_THREADS);
     #pragma omp parallel private(x) firstprivate(local_sum)
     {
          int i, id = omp_get_thread_num(); local_sum=0.0;
          int nthrds = omp_get_num_threads();
          double hoop = nthrds*step;
          for (i=id, x=(i+0.5)*step;i< num_steps; i=i+nthrds) {
            x += hoop;
            local_sum += 4.0/(1.0+x*x);
          }
          #pragma omp critical
          pi += local_sum * step;
     }
     printf("pi = %f \n", pi);
     return 0;
}
```

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The Scheduling Cause

- The schedule clause affects how loop iterations are mapped onto threads
  - schedule(static [,chunk])
    - Deal-out blocks of iterations of size "chunk" to each thread.
  - schedule(dynamic[,chunk])
    - Each thread grabs "chunk" iterations off a queue until all iterations have been handled.
  - schedule(guided[,chunk])
    - Threads dynamically grab blocks of iterations. The size of the block starts large and shrinks down to size "chunk" as the calculation proceeds.
  - schedule(runtime)
    - Schedule and chunk size taken from the OMP_SCHEDULE environment variable (or the runtime library)

The Scheduling Cause

Schedule Clause	When To Use
STATIC	Pre-determined and predictable by the programmer
DYNAMIC	Unpredictable, highly variable work per iteration
GUIDED	Special case of dynamic to reduce scheduling overhead

Least work at runtime : scheduling done at compile-time

Most work at runtime : complex scheduling logic used at run-time

Example 9: Scheduling

```
#include <omp.h>
#include <stdio.h>
static long num_steps = 100000000; double step;

int main ()
{
     int i; double pi, x, sum = 0.0;
     step = 1.0/(double) num_steps;
     #pragma omp parallel for private(x) reduction(+:sum) schedule(static,
     10000000)
     for (i=0;i< num_steps; i++){
          x = (i+0.5)*step;
          sum = sum + 4.0/(1.0+x*x);
     }
     Pi = sum * step;
     printf("pi = %f \n", pi);
     return 0;
}
```

Sequential: 2.12 seconds

1.31 seconds

10 chunks.

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Synchronization: ordered

- The **ordered** region executes in the sequential order
- Important for some scientific code and optimization code
  - Order of reduction may cause rounding differences


```
#pragma omp parallel private (tmp)
#pragma omp for ordered reduction(+:res)
      for (I=0;I<N;I++){
            tmp = NEAT_STUFF(I);
#pragma ordered
            res += consum(tmp);
      }
```

Synchronization Barrier

- **Barrier**: Each thread waits until all threads arrive


```
#pragma omp parallel shared (A, B, C) private(id)
{
      id=omp_get_thread_num();
      A[id] = big_calc1(id);
#pragma omp barrier
#pragma omp for
      for(i=0;i<N;i++){C[i]=big_calc3(i,A);}
#pragma omp for nowait
      for(i=0;i<N;i++){ B[i]=big_calc2(C,  i); }
      A[id] = big_calc4(id);
}
```

implicit barrier at the end of a for worksharing construct

No implicit barrier due to nowait

Implicit barrier at the end of a parallel region

“Single” Worksharing Construct

- The **single** construct denotes a block of code that is executed by only one thread (not necessarily the master thread).
- A barrier is implied at the end of the single block
  - can remove the barrier with a nowait clause


```
#pragma omp parallel
{
      do_many_things();
#pragma omp single
      {    exchange_boundaries();   }
      do_many_other_things();

}
```

```
#pragma omp parallel
{
      do_many_things();
#pragma omp single nowait
      {    exchange_boundaries();   }
      do_many_other_things();

}
```

Nested Parallelism

- **Q:** Is nested parallel possible with OpenMP?
- **A:** Yes. But be sure to understand why you want to use it.


```
#include <omp.h>
#include <stdio.h>
void report_num_threads(int level) {
     #pragma omp single
     { printf("L %d: # threads in team %d\n", level, omp_get_num_threads());}
}
int main() {
     omp_set_dynamic(0);
     #pragma omp parallel num_threads(2)
     {
          report_num_threads(1);
          #pragma omp parallel num_threads(2)
          {
               report_num_threads(2);
               #pragma omp parallel num_threads(2)
                    report_num_threads(3);
          }
     }
     return(0);
}
```


http://download.oracle.com/docs/cd/E19205-01/819-5270/aewbc/index.html

Nested Parallelism

- Compiling and running this program with nested parallelism enabled produces the following (sorted) output:


```
$ export OMP_NESTED=TRUE
$ ./experimentN
L 1: # threads in team 2
L 2: # threads in team 2
L 2: # threads in team 2
L 3: # threads in team 2
L 3: # threads in team 2
L 3: # threads in team 2
L 3: # threads in team 2
```



```
$ export OMP_NESTED=FALSE
$ ./experimentN
L 1: # threads in team 2
L 2: # threads in team 1
L 3: # threads in team 1
L 2: # threads in team 1
L 3: # threads in team 1
```

OpenMP Environment Variables

- OMP_SCHEDULE=algorithm
  - dynamic[, n]
  - guided[, n]
  - Runtime
  - **static[, n]**
- OMP_NUM_THREADS=num
- OMP_NESTED=TRUE|FALSE
- OMP_DYNAMIC=TRUE|FALSE

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Optimizing the Base Case

- Base case is usually the guts of the algorithm that computes on data in caches
- Should fit in registers
- Must use SIMD

Cost Model

- **Algebraic model**

  `+, -, /, *`

  `sin, cos, etc.`

- **Realistic model**
  - `+, -, /, *`
  - std libs (sin, cos, etc)
  - `array[i]`
  - `A.sum, A.prod`
  - `(double) x`
  - `func(…)`
  - `i < n,` compute
  - `i < n,` test and branch
  - { } unconditional branch

```
int func(int i) {
  return i+2;
}

struct A {
  double sum, prod;
};

A acc(int n, int array[]) {
  A res = {0.0, 1.0};
  for(int i=0; i<n; ++i) {
    A.sum = A.sum +
    (double)func(array[i]);
    A.prod = A.prod *
    (double)func(array[i]);
  }
  return res;
}
```

Cost Model (cont'd)

- **Algebraic model**

  cost = **3 n**

- **Realistic model**

  + and *
  2 int -> double
  4 a.x
  ++i
  i<n conditional jump
  2 func() calls

  cost = **19 n**

```
int func(int i) {
  return i+2;
}

struct A {
  double sum, prod;
};

A acc(int n) {
  A res = {0.0, 1.0};
  for(int i=0; i<n; ++i) {
    A.sum = A.sum + (double)func(i);
    A.prod = A.prod * (double)func(i);
  }
  return res;
}
```


6x discrepancy in cost

Using the Cost Model to Optimize

```
int func(int i) { return i+2; }

struct A { double sum, prod; };

A acc(int n, int array[]) {
  A res = {0.0, 1.0};

  for(int i=0; i<n; ++i) {
    A.sum = A.sum + (double)func(i);
    A.prod = A.prod * (double)func(i);
  }
  return res;

}
```


Cost = 19n

Using the Cost Model to Optimize I

```
int func(int i) { return i+2; }

struct A { double sum, prod; };

A acc(int n, int array[]) {
  double sum=0.0, prod=1.0;

  for(int i=0; i<n; ++i) {
    f = (double)(i+2);
    sum = sum + f;
    prod = prod * f;
  }
  A res = {sum, prod}
  return res;
}
```


Cost = 6n

Cost Reduction = closing down the gap

Using the Cost Model to Optimize II

```
int func(int i) { return i+2; }

struct A { double sum, prod; };

A acc(int n, int array[]) {
  double sum=0.0, prod=1.0;

  for(int i=2; i<n+2; ++i) {
    f = (double)(i);
    sum = sum + f;
    prod = prod * f;
  }
  A res = {sum, prod};
  return res;
}
```


Cost = 5n

Optimizations enable new optimizations

Using the Cost Model to Optimize III

```
int func(int i) { return i+2; }

struct A { double sum, prod; };

A acc(int n, int array[]) {
  double sum=0.0, prod=1.0;
  #pragma unroll(4)
  for(int i=2; i<n+2; ++i) {
    f = (double)(i);
    sum = sum + f;
    prod = prod * f;
  }
  A res = {sum, prod};
  return res;
}
```


Cost = 3.5n

Final result: 3.5n vs 19n

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Cost Reduction: A Compiler Problem

- **Solution:** "Human Compiler"
- Compilers often fail on complex codes (many assumptions are violated)

- Optimizations
  - **Strength reduction**
  - **Function inlining**
  - **Loop unrolling**
  - **Common subexpression elimination**
  - **Load/store elimination**
  - **Table lookups**
  - **Branch elimination**

Strength Reduction

```
for i = 1..n
    sum = sum + a[i] / c;
```


division is more expensive than multiplication

```
double c_inv = 1/c;
for i = 1..n
    sum = sum + a[i] * c_inv;
```

Expensive operations:
/, %, sin, cos, log

Function Inlining

```
double f(a) { return a/c; }
.
.
for i = 1..n
    sum = sum + f(a[i])
```


```
for i = 1..n
    sum = sum + a[i] / c;
```

Now strength reduction can apply

Loop Unrolling

```
for i = 1..n
    sum = sum + a[i]
```


sequential locality

```
for i = 1:4:n
    sum = sum + a[i] + a[i+1] + a[i+2] + a[i+3]

// remaining iterations
for i = i:n
    sum = sum + a[i]
```

Often enables other optimizations

Common Sub-expression Elimination

```
for j = 1..m
  for i = 1..n
    sum = sum + cos(j*PI/180)*a[i];
```

```
for j = 1..m
  double c = cos(j*PI/180);
  for i = 1..n
    sum = sum + c*a[i];
```

Table Lookups

```
for j = 1..m
  for i = 1..n
    sum = sum + cos(j*PI/180)*a[i];
```


```
for j = 1..m
  double c = COS_TAB[j];
  for i = 1..n
    sum = sum + c*a[i];
```

Load/Store Elimination

Loop Merging

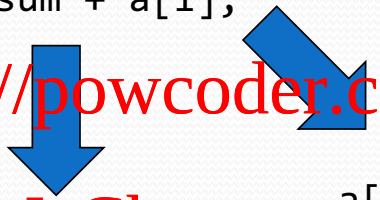

```
for i = 1..n
    sum = sum + f(a[i]);
for i = 1..n
    prod = prod * f(a[i]);
```

```
for i = 1..n
    sum = sum + f(a[i]);
    prod = prod * f(a[i]);
```

One of the most important optimizations!
Almost always enables other optimizations.

Branch Elimination

```
for i = 1..n
   if(i != except)
      sum = sum + a[i];
```



```
for i = 1..except-1
   sum = sum + a[i];
for i = except+1..n
   sum = sum + a[i];
```

```
a[except] = 0.0;
for i = n
   sum = sum + a[i];
```

What we have discussed in the last 2 lectures

Fast Platforms

- **Multicore platforms**
- **Manycore platforms**
- **Cloud platforms**

+

Good Techniques

- **Data structures**
- **Algorithms**
- **Software Architecture**

- **OpenMP Abstractions:**
  - Help establish a mental model for the programmers
  - Make it easier to write parallel code
  - **Performance depend on deep understanding of the implementation platform**