Cilk™ Plus in GCC

GNU Tools Cauldron 2012

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Presentation Outline

- Introduction
- Cilk Plus components
- Implementation
- GCC Project Status
- The Next steps and Community Contribution

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Why Parallel Programming?

- Most computers today contain multiple cores.
  - More power efficient to use multiple compute elements than a monolithic processor with high clock rates.
- Vector units and SIMD instructions are present in most modern microprocessors
  - AVX (Intel), NEON (ARM), MIPS-3D (MIPS), Altivec (Motorola), Tilera (tilepro), Tensilica (xtensa), …
- Future Trends:
  - Transistor densities continue to increase
  - High throughput while consuming less power
  - Complex handheld devices are emerging ➔ low-energy

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Parallel Programming

- Parallel programming is necessary to fully utilize today's processors
- The application must keep the processors busy while achieving high-performance and consuming less power.
- Parallel programming can be hard!
  - Combining threads and locks introduces errors & performance issues
  - Programming with threads is tedious and *non-expressive*
  - Programming directly with threads often leads to undesirable non-determinism
- The vectorizer may need help from programmer for C/C++ programs due to pointer aliasing

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Cilk Plus

The Intel ® Cilk™ Plus specification is a set of C/C++ extensions for programming multicore vector processors that:

- Incorporates vector and task level parallelism
- Describes the semantics of a parallel program so that the compiler can apply thread-level and vector-level parallelism
- Has been applied to GCC

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Cilk Plus Implementation

- Fully implemented in Intel's compiler (ICC)
- A branch in GCC was opened in August 2011
- All features of initial ABI have been implemented in Cilk Plus GCC

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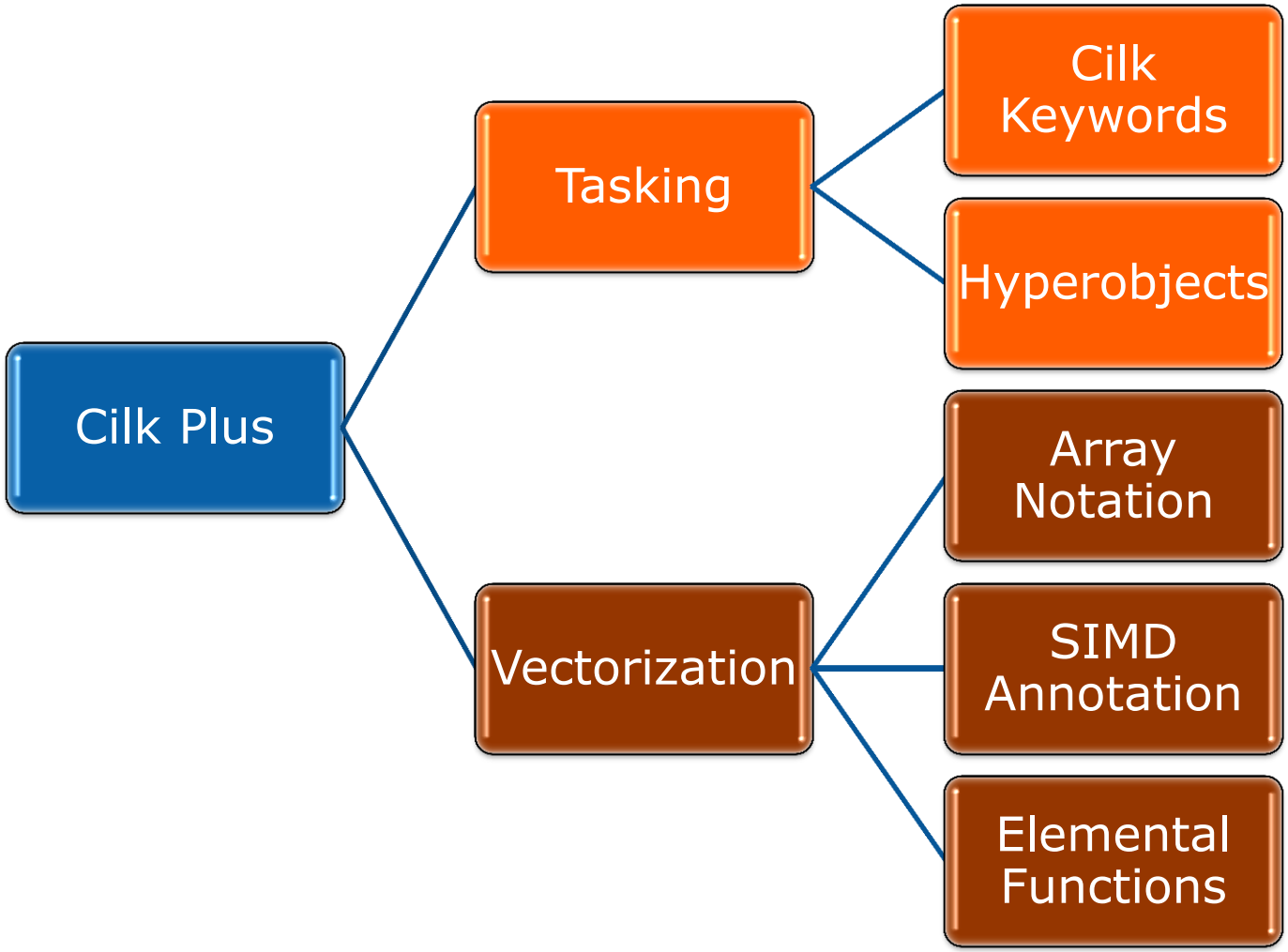
Cilk Plus Components



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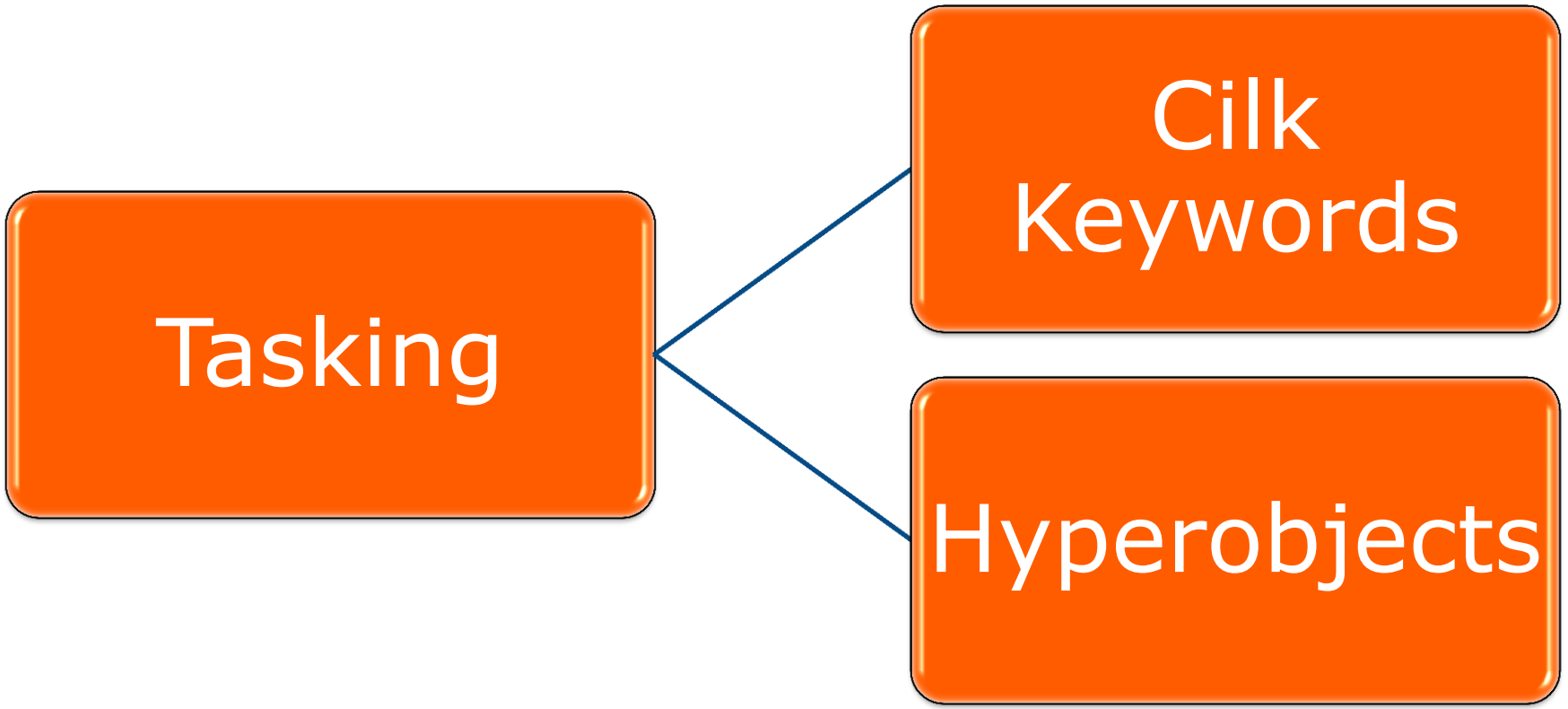
Cilk Plus Tasking Components



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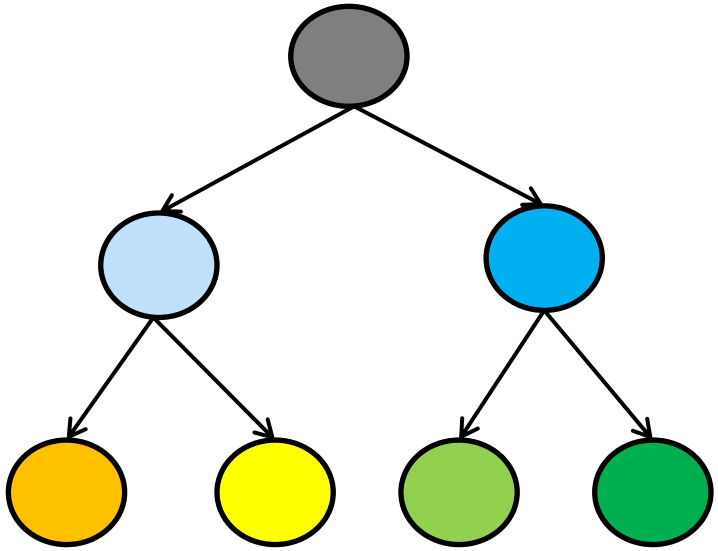
Tree Walk Example

```
int tree_walk(node *n)
{
    int a = 0, b = 0;
    if (n->left)
      a = tree_walk(n->left);
    if (n->right)
      b = tree_walk(n->right);
    int c = f(n->value);

    return a + b + c;
}
```



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Parallel Tree Walk

```
#include <cilk/cilk.h>
int tree_walk(node *n)
{
    int a = 0, b = 0;
    if (n->left)
      a = cilk_spawn tree_walk(n->left);
    if (n->right)
      b = cilk_spawn tree_walk(n->right);
    int c = f(n->value);
    cilk_sync;
    return a + b + c;
}
```


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Parallel For Loop

```
for (int i = start; i < finish; i += stride)
 { /* Body of loop uses i */ }
f();
```

Iterations can execute in parallel.

All iterations must complete before f() executes

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cilk_for Loop

```
cilk_for (int i = start; i < finish; i += stride)
    { /* Body of loop uses i */ }
f();
```

- Runtime uses dynamic load-balancing
- Iterations must be independent -- compiler can apply data-parallel optimizations such as vectorization.
- Loop control variable can be any random access iterator.

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Interaction with Cilk Runtime

Cilk Runtime is responsible for thread creation

- **`cilk_spawn`** gives the runtime *permission* to continue before the called function (child) returns.
  - Low cost (5x to 10x cost of a function call)
  - Code is *processor oblivious*: the number of cores is not specified.
  - If no available resources, then child executes serially.
  - A work-stealing scheduler may *steal* the continuation in the caller and run it asynchronously.
- **`cilk_for`** gives the runtime *permission* to run iterations in parallel
- **`cilk_sync`** does not cause any thread to stall
  - A worker thread just finds other work to steal.
  - No global barrier is implied.

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Reducer Hyperobjects

- "Traditional" reduction on a parallel for loop:

```
long a[sz];
cilk::reducer_opadd<long> sum(0);
cilk_for (std::size_t i = 0; i < sz; ++i)
    sum += a[i];
```

Warning: reducer_opadd<float> would not be fully deterministic!

Parallel accesses each get their own "view" of sum

- Generalized reduction for *any code* executing in parallel:

```
cilk::reducer_list_append<int> lst;
void tree_walk2(node *n) {
  if (n->left) cilk_spawn tree_walk2(n->left);
  if (n->right) cilk_spawn tree_walk2(n->right);
  lst.push_back(f(n->value));
}
```

Final list has same order as for serial execution!

- You can define your own reducer types.

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Tasking Summary

- Using 3 simple keywords a serial program can be converted to a parallel program
- The user need not worry about the processor architecture.
  - It is the runtime's job!
- Hyperobjects help achieve serial semantics in a parallel program

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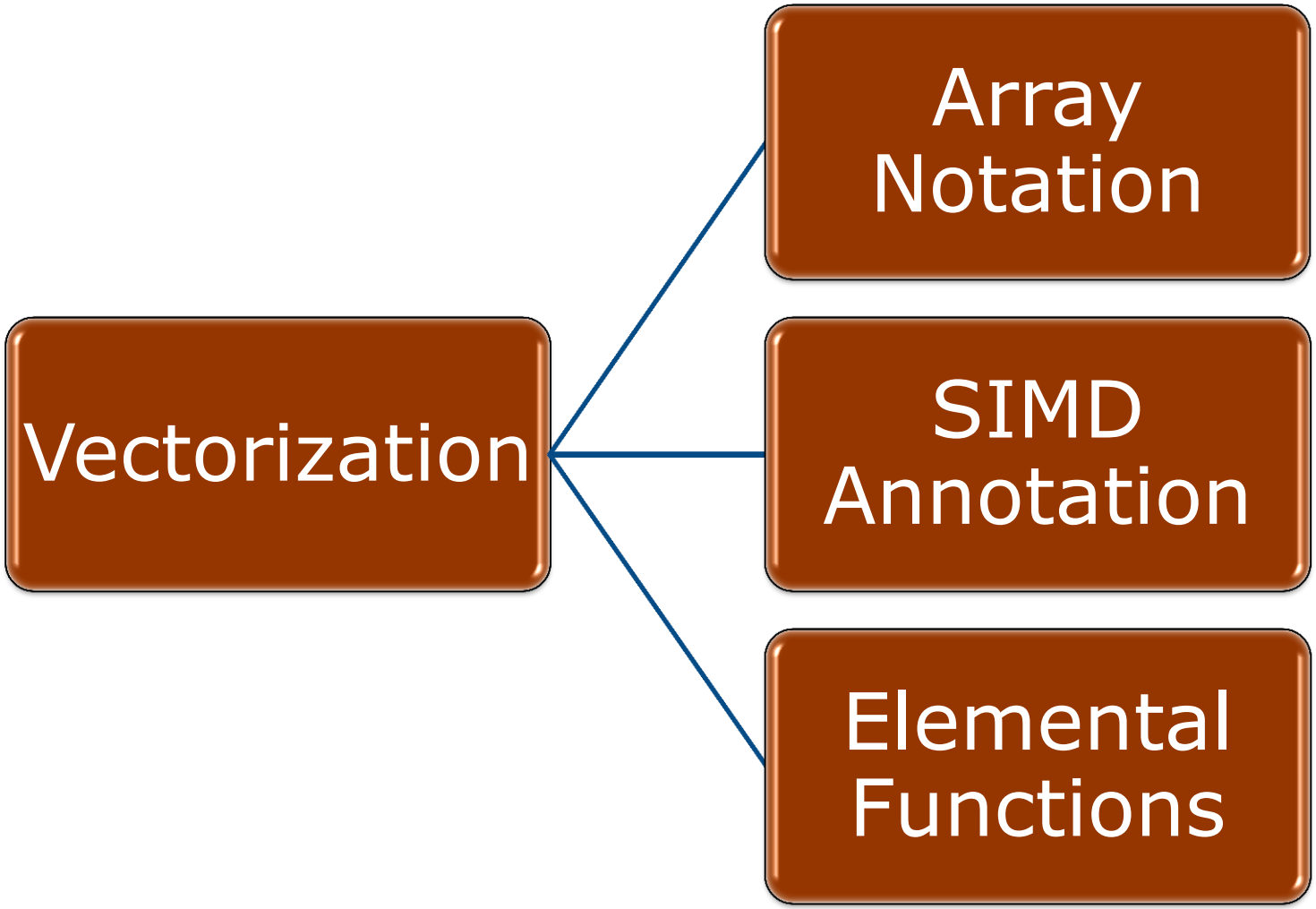
Cilk Plus Vectorization Components



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Array Notation

- Let programmer specify parallel intent
  - Give license to the compiler to vectorize

```
// Set y[i] ← y[i] + a * x[i] for i∈[0..n)
void saxpy (float a, float x[], float y[], size_t n)
{
    y[0:n:1] += a * x[0:n:1];
}
```

It also works on pointers

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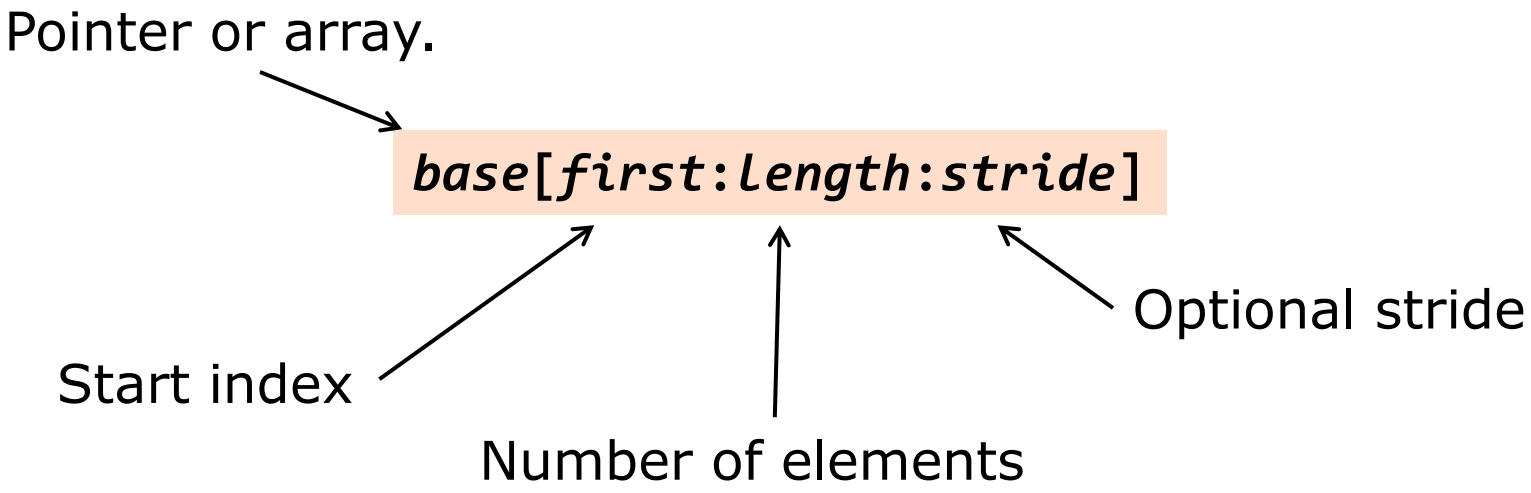
Array Section Triplet



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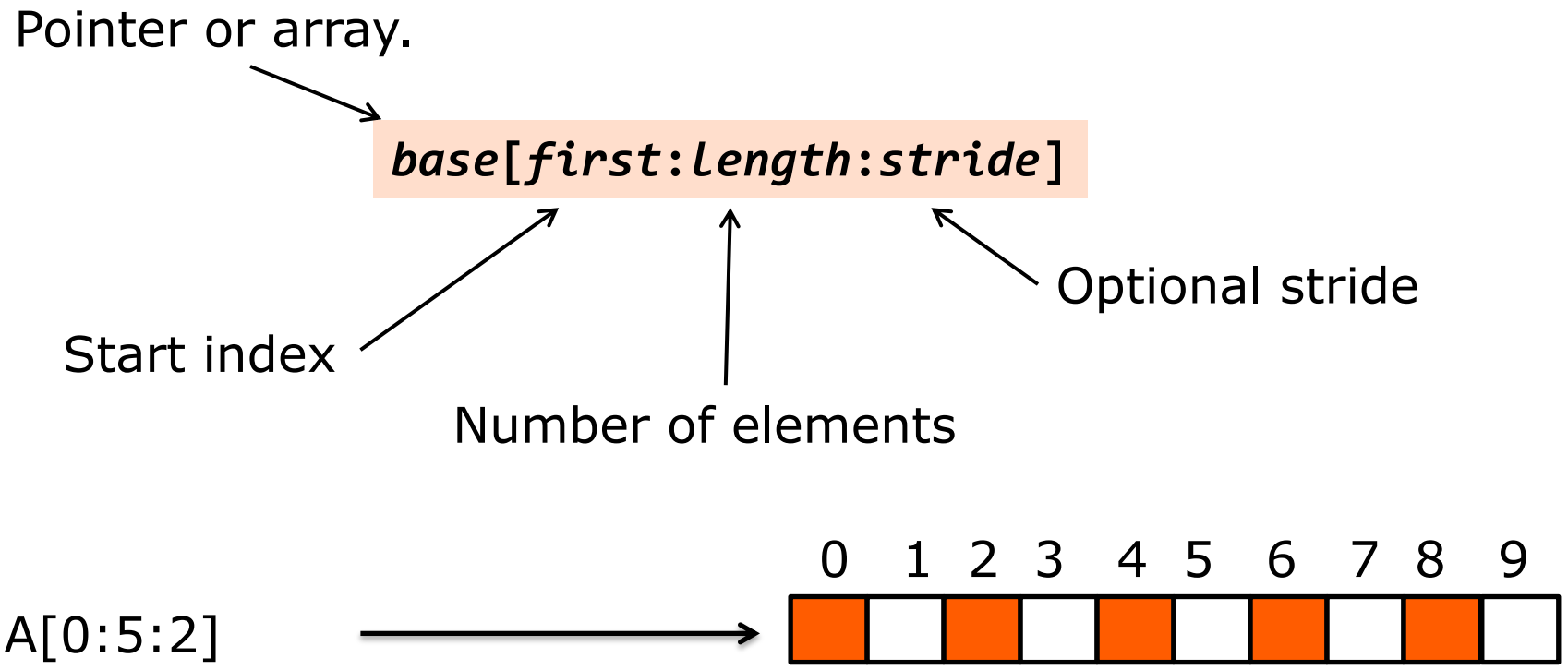

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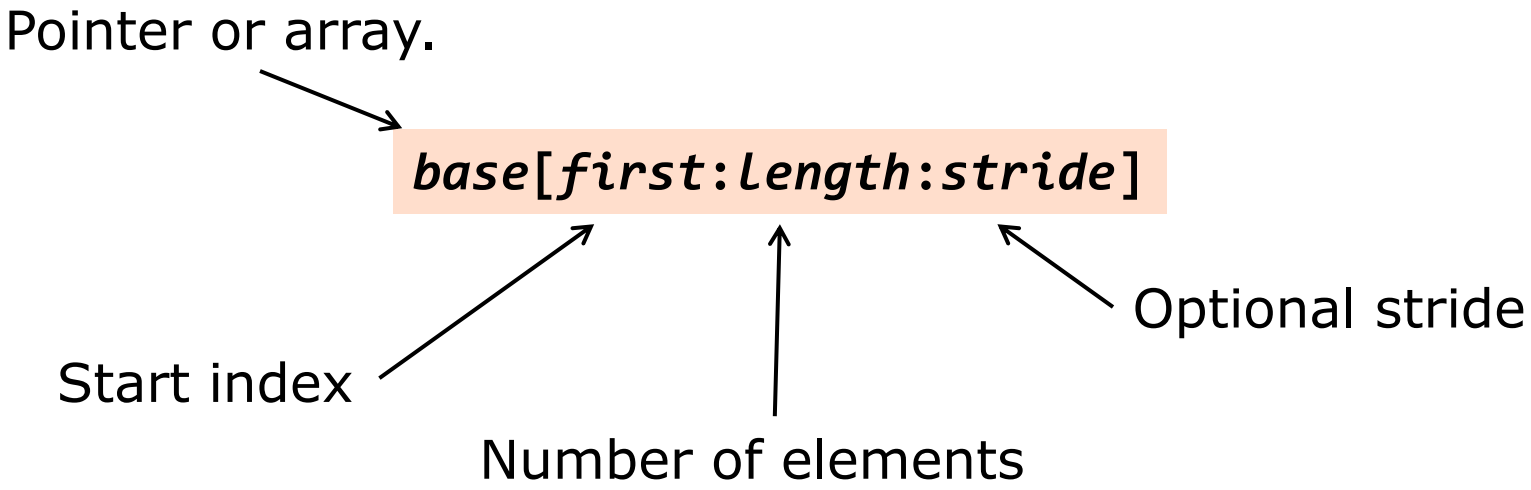

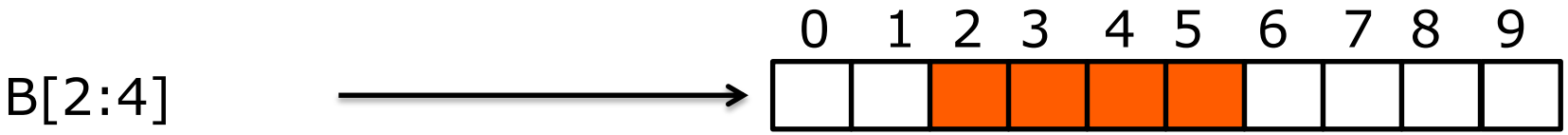

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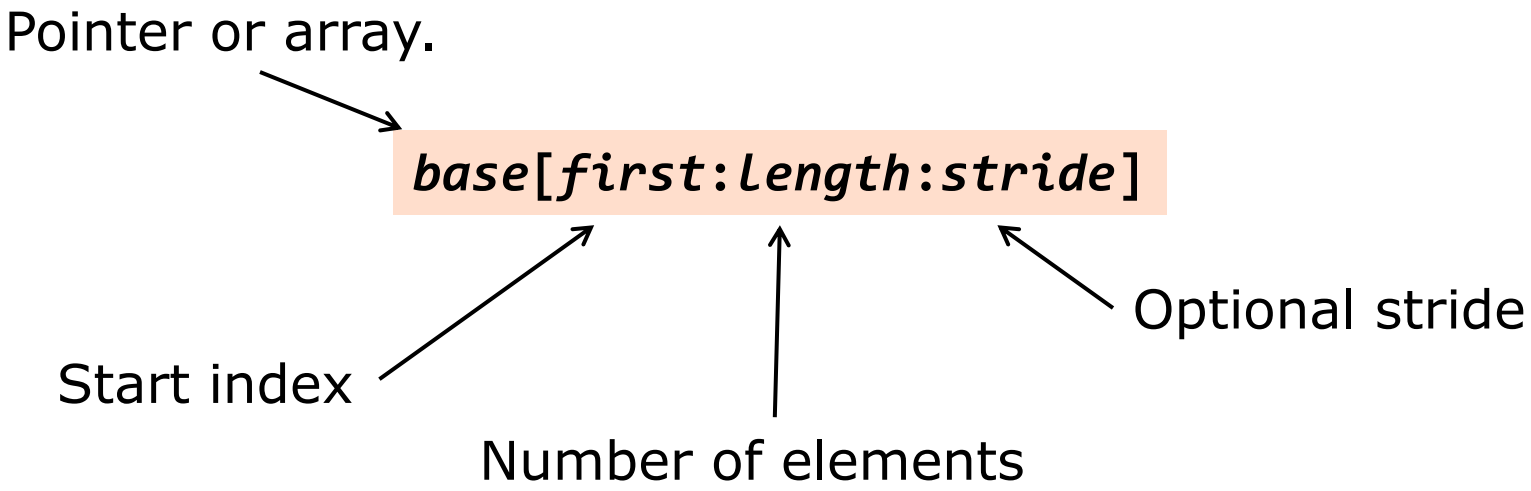

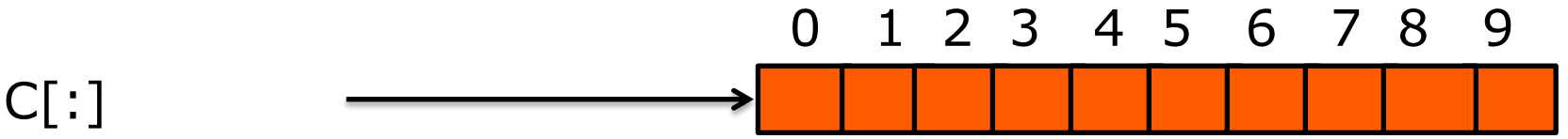

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Array Notation Decomposition

```
int A[10], *B;
A[1:5:2] = B[1:5];
```

```
for (i = 0; i < 5; i++)
  A[(i*2) + 1] = B[(i*1) + 1];
```

```
int A[10];
A[:] = 5;
```

```
for (i = 0; i < 10; i++)
  A[i] = 5;
```

```
int *B;
B[:] = 5;
```

```
error!! one must specify the
start and length of access for
pointers!
```


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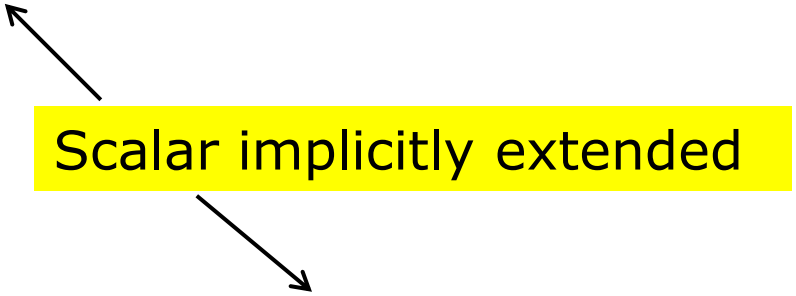
More Examples

- Update m×n tile with corner [i][j].

```
Vx[i:m][j:n] += a*(U[i:m][j+1:n]-U[i:m][j:n]);
```



- Function call

```
theta[0:n] = atan2(y[0:n],1.0);
```

- Gather/scatter

```
w[0:n] = x[i[0:n]];
y[i[0:n]] = z[0:n];
```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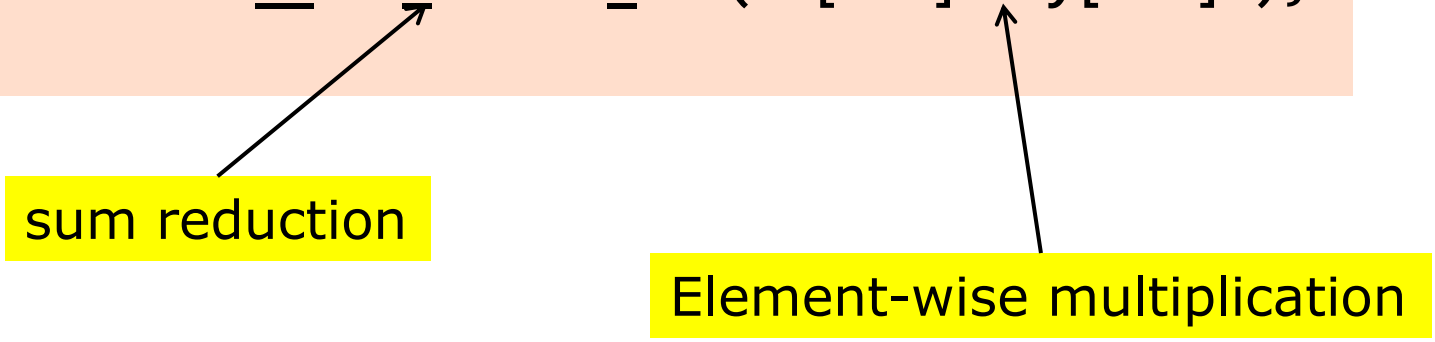
Built-in Reduction Functions

- Built-in reduction operation for common cases
  +, *, min, index of min, etc.
- User-defined reductions allowed too

```
float dot( float x[], float y[], size_t n )
{
    return __sec_reduce_add( x[0:n] * y[0:n] );
}
```



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Array Notations with Conditionals

- Array notation can be used within conditionals.
- A vectorizing compiler can generate a mask that allows vector computations based on the condition.

```
int array_abs (int *A, int N)
{

  if (A[0:N] < 0)
    {
      A[0:N] = A[0:N] * -1;
    }
}
```

```
int array_abs (int *A, int N)
{
for (i = 0; i < N; i++)
  if (A[i] < 0)
    {
      A[i] = A[i] * -1;
    }
}
```


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SIMD Annotation

- Loop annotation informs the compiler that vectorized loop will have same semantics as serial
- Used to break dependencies that user knows are unnecessary.
- Additional clauses for reductions and other vectorization guidance (borrowed from OpenMP*)

```
int func (int *p, int *q) {
#pragma simd
  for (int ii = 0; ii < 10000; ii++)
    {
      *(a+ii) = *(p+ii) + *(q+ii);
    }
}
```


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How do we vectorize these scenarios?

- File 1 (main.c)

```
extern int my_add (int, int);
for (int i = 0; i < 10000; i++)
  {
     z[i] = my_add (x[i], y[i]);
  }
```

This for-loop cannot be vectorized due to a function call inside it…

- File2 (add.c)

```
int my_add (int x, int y)
{
   return x + y;
}
```

….but this function call can operate on vector registers & return a vector value while achieving correct result

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Elemental Functions

- A way to allow vectorization across function boundaries
- The user implements a **scalar version** of the function with an appropriate annotation
- The compiler creates a vector version of the function
- Clauses available to describe the target processor and the behavior of the function parameters
- A good application: Writing function libraries

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Elemental Functions - Example

- Defining an elemental function:

```
                          double option_price_call_black_scholes(
    double S, double K, double r, double sigma, double time)
{
    double time_sqrt = sqrt(time);
    double d1 = (log(S/K)+r*time)/(sigma*time_sqrt) +
        0.5*sigma*time_sqrt;
    double d2 = d1-(sigma*time_sqrt);
    return S*N(d1) - K*exp(-r*time)*N(d2);
}
```

- Invoking the elemental function:

```
for (i = 0; i < N; i++)
  call[i] = option_price_call_black_scholes(S[i],K[i],r,
                                                sigma, time[i]);
```

- Array notations are also allowed

```
call[:] = option_price_call_black_scholes(S[:], K[:], r, sigma, time[:]);
```


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Vectorization Summary

- Array notation provides a trivial method to write parallel code
- SIMD annotation provides simple pragmas that can be used to vectorize loops by breaking outside dependency
  - Code is portable across compilers
- Elemental function allows vectorization across function boundaries.

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- Cilk Plus Vector components
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Performance Status

- Overall, Cilk Plus GCC performs as expected on several internal benchmarks
- We noticed one problem: aobench
  - ICC compiled executable was significantly faster than the gcc-compiled one.
  - Upon investigation we found a 2 way nested loop that ICC vectorized and GCC just emitted scalar code.

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AO bench: Ambient Occlusion Renderer

- Small program for benchmarking real-world floating point performance.
- Case study for combining task and data parallelism in Cilk Plus.
- Parallelized in 1 day using Cilk Plus
- Original Serial code: http://code.google.com/p/aobench/

http://software.intel.com/en-us/articles/data-and-thread-parallelism/

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AO Bench Kernel

- Aobench has a huge 2-way nested for-loop that was the hottest part of the code.

```
Compute ambient occlusion ()
{
  compute an ortho-basis for intersect pt normal ()
  for number of samples wide
    {
      for number of samples high
        {
          compute random ray using cosines, sines
          and square roots.
          occlusion += intersection of scene objects ()
        }
    }
}
```


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AO Bench Analysis

- When we inlined this function and some of its callees, several dependencies (due to temporary assignments) in the code disappear and the loops can be vectorized.

- We hand-vectorized the code and we were able to get about half the difference back

- Remaining difference due to vector transcendentals
  - Sine and cosines were used extensively in the for-loop.
  - GCC was not able to insert vector version of these functions

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Cilk Plus Status Summary

- Cilk Plus is a great set of language extensions to extract both vector-level and task-level parallelism
- Cilk Plus GCC is a branch of GCC live-sources.
- The runtime has been released as free software and is available with Cilk Plus GCC.
- All features of initial Cilk Plus ABI (ABI 0) have been implemented.
  - Update to the most recent ABI (ABI 1) is in progress.
- Proposed for inclusion in the next C++ Standard
- Looking forward to have Cilk Plus adopted into trunk

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Community Contributions

- Contributions from GCC community are welcome and encouraged.
- We would like adoption and feedback
- Wish list:
  - Better vectorization support
  - Optimize existing procedures.
  - Ports to other architectures

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Cilk Plus Related Websites

- Cilk Plus Website: www.cilkplus.org
- Language Specification and ABI:
  http://software.intel.com/en-us/articles/intel-cilk-plus-specification/
- Cilk Plus GCC Branch:
  - svn://gcc.gnu.org/svn/gcc/branches/cilkplus

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