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C++ Language Constructs for Parallel Programming

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Goals

- To solicit interest in adding language constructs for parallelism to C++.
- To present the concepts in Intel® Cilk™ Plus as a basis for potential changes to C++.
- To create a common understanding of the factors that should influence the design of such constructs.

- **This presentation is not a proposal.**
  - Today we are presenting concepts
  - Next meeting we will bring proposals

Agenda

- About Parallelism
- Existing approaches
- An overview of Intel® Cilk™ Plus
- Desirable qualities of a parallel extension
- Implementation
- Conclusion

Agenda

- **About Parallelism**
  - Why parallelism?
  - Why parallelism constructs?
  - Task and data parallelism
- Existing approaches
- An overview of Intel® Cilk™ Plus
- Desirable qualities of a parallel extension
- Implementation
- Conclusion

Why Parallelism?

- Virtually all computers today contain multiple cores and vector instruction sets, and mobile devices are rapidly catching up.
- Many-core architectures such as Intel's MIC and modern GPUs are being tapped for computation.
- It is more power efficient to use multiple compute elements than to increase the clock rate of a single element.
- These developments will continue/accelerate
  - Transistor densities continue to increase
  - Mobile and data center both demand more speed with less power consumption
  - Expect 1000s of cores to become commonplace

Why Add Parallelism Constructs to C++?

- Parallel programming is **Hard!**
- Without standard support, concurrent programming often falls back on error-prone, ad-hoc protocols.
  - Similar to parameter-passing protocols before Fortran
- Programming directly with threads often leads to undesirable non-determinism[1]
- Threads and locks are not composable: Combining components introduces errors (e.g., deadlocks) or performance problems (e.g., resource contention).

Multicore and vector parallelism technologies have matured. It is time that we give C++ programmers access to them.

[1]Bocchino et. al., *Parallel Programming Must Be Deterministic by Default*

Task and data parallelism

- Task parallelism:
  - Performs separate operations in parallel
  - Takes advantage of multiple CPUs and hardware threads.
- Data parallelism:
  - Performs essentially the same operation on multiple data elements in parallel
  - Takes advantage of all HW resources: vector units and GP GPUs as well as multiple CPUs.
- Other parallelism (not explored in this presentation)
  - Coordination languages
  - Distributed parallelism
  - Parallel workloads

Threads and Tasks

- **Threads** are used for *coarse-grained* ***concurrency***
  - Concurrency is *mandated* – forward-progress is expected on all (non-blocked) threads.
  - Expensive to create – usually long-lived
  - Best for user interfaces, independent workloads (e.g., web server sessions), client-server workloads, etc.
- **Tasks** are used for *fine-grained* ***parallelism***
  - Concurrency is *allowed* but not mandated – only one task at a time is typically required to make forward progress
  - Inexpensive to create – can be very short-lived
  - Best for parallelizing an algorithm to take advantage of available parallel hardware resources.

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Existing approaches to parallelism in C++

- OpenMP*
- Intel® Threading Building Blocks™ (Intel® TBB) and Microsoft Parallel Patterns Library (PPL)
- std::thread, std::async, std::future
- Auto parallelization
- CUDA* and OpenCL*

- **Intel® Cilk™ Plus**
  - Intel believes that Cilk Plus can be the basis for a set of standard language features for parallelism in C++
  - Based on 15+ years of research (MIT, CMU, GA Tech)
  - Has both task and data parallel constructs
  - Well structured, composable, and has serial semantics

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- About Parallelism
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- **An overview of Intel® Cilk™ Plus**
  - Task-parallel features
  - Data-parallel features
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Intel® Cilk Plus

Parallel tasks	• Easy to learn: 3 keywords (C & C++) • Tasks, not threads • Load balancing
Hyper Objects	• Mitigate data races on non-local variables
Array notations	• Data-parallel array operations • Targets SIMD, GPU
Elemental Functions	• Data-parallel function mapping
SIMD Annotation	• Vectorization annotation for loops • Currently expressed as a pragma

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 Intel® Cilk™ Plus

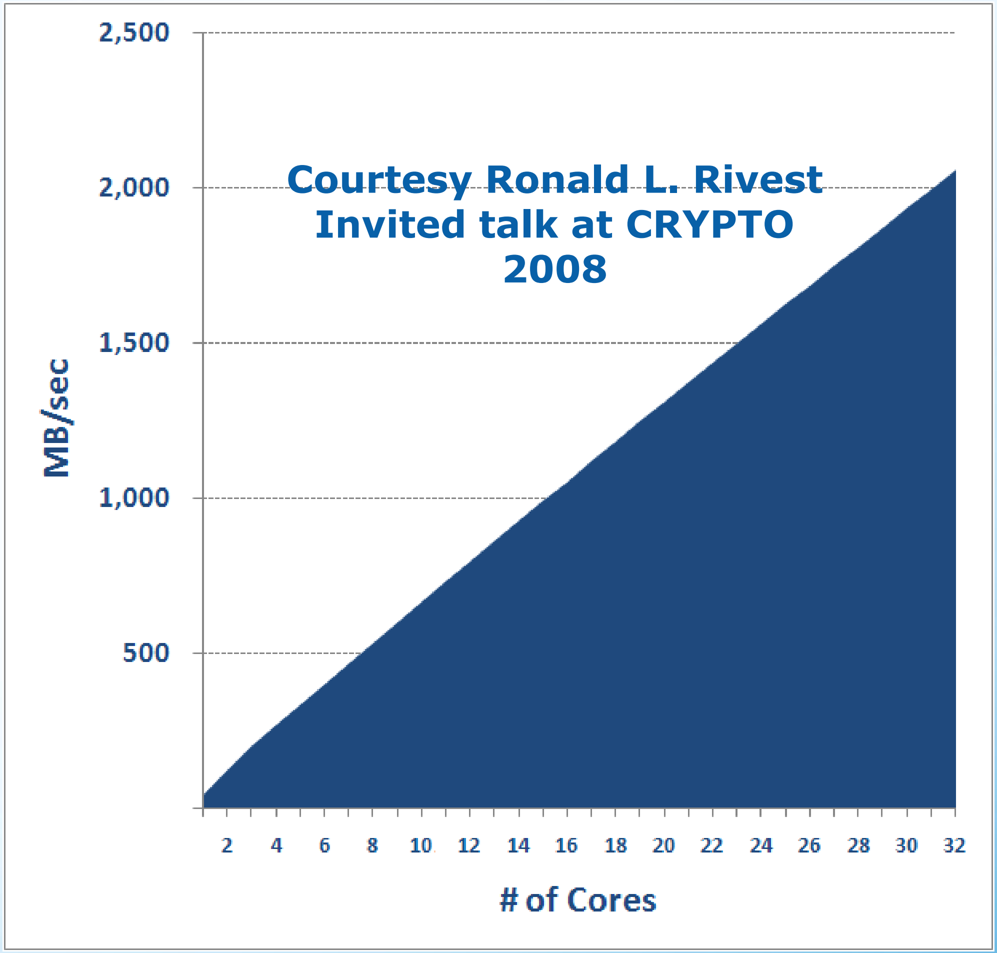
AObench Video	
Serial 0.67 FPS 1.00 X	Array Notation 1.42 FPS 2.10X
Intel Cilk tasks 3.30 FPS 4.90 X	Intel Cilk tasks + Array Notation 6.89 FPS 10.25 X

3.2GHz Intel® architecture code-name Nehalem (8 hyperthreads)
32-bit Win 7, 3GB RAM

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

MD6: Cryptographic Hash Function

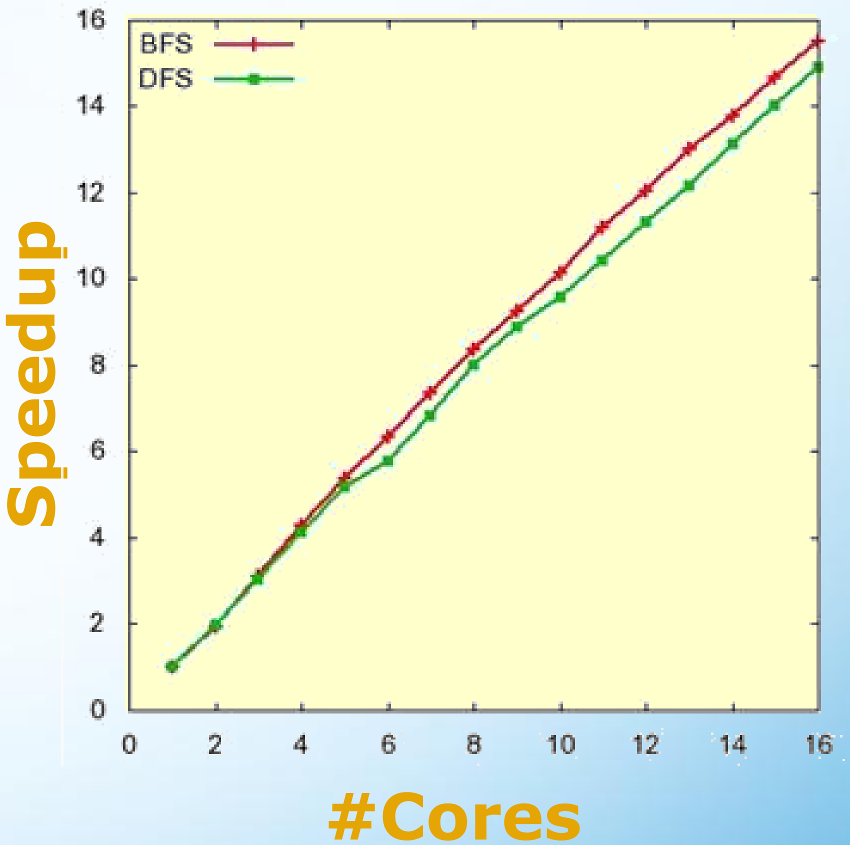
- Cryptographic hash function submitted to NIST competition
- Leverages large memory and multicore CPU’s
- Multicore-enabled in 1 day (Cilk Arts Cilk++ SDK)
- HP DL785
  - 8 Quad-Core Opterons
  - 1.1 GHz
  - 16 GB RAM



http://software.intel.com/en-us/articles/intel-cilk-sdk-resource-library/

Murphi: Model Checker

- Finite-state-machine verification tool developed at Stanford University.
- 3 programmer-months to ship a production-quality multicore-enabled version with Cilk Arts Cilk++ SDK.
- Employs parallel breadth-first and depth-first search algorithms on a sparse graph.



http://software.intel.com/en-us/articles/intel-cilk-sdk-resource-library/

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- About Parallelism
- Existing approaches
- **An overview of Intel® Cilk™ Plus**
  - **Task-parallel features**
    - `cilk_spawn`, `cilk_sync` and `cilk_for` keywords
    - hyperobjects
  - Data-parallel features
    - array notation
    - elemental functions
    - pragma simd
- Desirable qualities of a parallel extension
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Serial Tree Walk

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

    return a + b + c;
}
```

cilk_spawn and cilk_sync Keywords

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

Asynchronous recursive call to tree_walk

Call to f() can run in parallel with recursive tree walks

Implicit sync at the end of every function keeps code well structured

cilk_for Loop

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

Iterations can execute in parallel.

All iterations complete before f() executes

```
cilk_for (iterator x = c.begin(); x != c.end(); ++x)
    { /* Body of loop uses *x */ }
f();
```

Random-access iterator

- A high-quality implementation will use dynamic load-balancing for unbalanced iterations.
- Iterations are independent -- compiler can apply data-parallel optimizations such as vectorization.

Spawning is not 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) No new threads
  - Code is *processor oblivious*: the number of cores is not specified.
  - If no available resources, then child executes serially.
  - A work-stealing scheduler (described later) may *steal* the parent 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

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(0);
void tree_walk2(node* nodep) {
  if (nodep->left) cilk_spawn tree_walk2(nodep->left);
  if (nodep->right) cilk_spawn tree_walk2(nodep->right);
  lst.push_back(f(nodep->value));
}
```

Final list has same order as for serial execution!

- You can define your own reducer types.

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- About Parallelism
- Existing approaches
- **An overview of Intel® Cilk™ Plus**
  - Task-parallel features
    - cilk_spawn, cilk_sync and cilk_for keywords
    - hyperobjects
  - **Data-parallel features**
    - array notation
    - elemental functions
    - pragma simd
- Desirable qualities of a parallel extension
- Implementation
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Array Notations

- Concise data-parallel notation encourages effective exploitation of SIMD, multi-core, and/or GPU
- The [:] operator delineates an *array section*:

  array-expression[*lower-bound* : *length* : *stride*]
- Each argument to [:] may be omitted:
  - Default *lower-bound* is 0
  - Default *length* is the length of the array (if known)
  - Default *stride* is 1 (second colon may be omitted)
- Array sections can be used with unary and binary operators for element-by-element computation:

```
a[10:count] = b[0:count] + c[0:count:2];
```

- Intrinsic functions operate on entire array sections

Array Notation Example

- Serial Example

```
float dot_product(unsigned int sz,
                  float A[], float B[]) {
    float dp=0.0f;
    for (int i=0; i<sz; i++)
         dp += A[i] * B[i];
    return dp;
}
```

- Array Notation Version

```
float dot_product(unsigned int sz,
                  float A[], float B[]) {
    return __sec_reduce_add(A[0:sz] * B[0:sz]);
}
```

Intrinsic reduction

Array Section

Element-wise multiplication

Rank and Shape

- No new type(s) for array sections
  - Type of an array section is just the element type
  - Additionally, an array section has rank and shape
- Rank: number of array-section operators on a single array
- Shape: vector of lengths of array sections
  - Conceptual, not concrete
  - Rank is the length of the shape vector

Expression	Rank	Shape
`a[0]`	0	
`a[0:n]`	1	n
`a[0][i:10]`	1	10
`a[i:n][j:m]`	2	n × m

Masked vector operations

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

```
if (a[:] > b[:]) {        // Create a (logical) bit-mask, M
    c[:] = d[:] * e[:];   // For indexes where M contains 1
} else {
    c[:] = d[:] * 2;      // For indexes where M contains 0
}
```

Elemental Functions

- A general construct to express data parallelism:
  - Write a function to describe the operation on a single element
  - Invoke the function across a parallel data structure (arrays) or from within a vectorizable loop.
  - Implementation: A high-quality compiler vectorizes across consecutive invocations of the function
- Polymorphic: a vectorizing compiler may create both array and scalar versions of the function.
- Function parameters can be `varying`, `uniform`, `linear`
  - Allows mapping to the most efficient load/store available.
  - Allows optimization of address computations.
- Authoring the function is independent of its invocation
  - The function can invoked on scalars, within serial for or cilk_for loops, using array notation, etc..

Elemental Functions - Example

- Defining an elemental function:

```
__declspec (vector) 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);
}
```

Compiler breaks data into SIMD vectors and calls function on each vector

- Invoking the elemental function:

```
// The following loop can also use cilk_for
call[0:N] = option_price_call_black_scholes(S[0:N], K[0:N], r,
                                            sigma, time[0:N]);
```

#pragma SIMD

- Loop annotation informs the compiler that vectorized loop will have same semantics as serial loop:

```
void f(float *a, const float *b, const int *e, int n)
{
#pragma simd
    for (int i = 0; i < n; ++i)
        a[i] = 2 * b[e[i]];
}
```

Potential aliasing and loop-carried dependencies would thwart auto-vectorization

- Currently implemented as a pragma, but other methods of annotating the loop can be considered.
- Additional clauses for reductions and other vectorization guidance (borrowed from OpenMP*)

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- An overview of Intel® Cilk™ Plus
- **Desirable qualities of a parallel extension**
  - Structured Parallelism, Determinism & Serial Semantics
  - Why a language extension instead of a library-only approach?
- Implementation
- Conclusion

Desirable qualities of a parallel extension

- Minimal changes to the existing language
- Efficient exploitation of all forms of mainstream hardware parallelism
- Hardware independent and scalable to future hardware (e.g. more cores & wider vector units).
- Composable (parallelism in library components does not introduce errors or performance issues)
- **Support for building programs that are easy to reason about**
  - Clean, expressive, syntax
  - Serial semantics
  - Deterministic results

Structured Parallelism and Determinism

- The biggest challenge in writing correct programs is making it possible to reason about your program.
- Experience has shown that *structure* is an important quality for parallel constructs that can be reasoned about. (Compare loops vs. goto.)
- Ideally, a parallel program would be as easy to reason about as a serial program.
- A good parallelization model abstracts away as much non-determinism as possible.
  - Language constructs should favor determinism
  - Non-determinism should be available for when the need arises.

Benefits of Structured Parallelism

- Composability
  - Given a call to f(), the caller doesn't need to know whether f() uses cilk_spawn or array operations.
  - Scalable to large codebases
- Tools
  - The **Cilkscreen** race detector is guaranteed to find races in any ostensibly deterministic Cilk Plus program.
  - The **Cilkview** scalability analyzer can determine how your program will scale to more cores.
- Optimization
  - The compiler can determine invariants only when the parallel constructs are fully structured

Serial Semantics

- Definition: a deterministic (race-free) program has the same semantics when running on one HW thread or many HW threads
- Dramatically simplify the task of reasoning about the program logic.
- Simplify the task of converting a serial program to a parallel program
- Allow serial debugging separate from parallel debugging.
- Allow tools and debuggers to discover many properties of a program – even parallel properties – by running the program serially (i.e., on one core)

Why a language extension instead of a library-only approach?

- Serial semantics: Structure is enforced by the compiler.
- Simpler syntax: A few keywords and operators can take the place of a large number of templates
- C compatibility: we want to propose similar extensions to C and C++.
- Implementation options: Difficult to implement lazy task creation using a library approach.
- Optimization: Huge opportunities for the compiler to apply algorithms and heuristics to the parallel code, e.g., much more effective vectorization.

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- **Implementation**
  - Load balancing and work-stealing schedulers
  - Implementation experience
- Conclusion

Work Stealing

This Slide is not meaningful without animation

```
void f()
{
   cilk_spawn g();
   work
   work
   work
   cilk_sync;
   work
}
```

steal!

```
void g()
{
   work
   work
   work
}
```

Worker A

Worker B

Worker ?

Why Work Stealing?

- A work-stealing scheduler can be shown mathematically to be nearly optimal for a program with sufficient parallelism.
  - Gracefully handles control-flow and data divergence.
  - Used by most modern parallel programming systems
- Intel® Cilk™ Plus implements *lazy task creation*
  - Scheduler performs parent stealing, not child stealing
  - Serial semantics, even when using futures or the like.
  - Deterministic memory use
- Any C++ parallel extension should support (though not necessarily require) a work stealing scheduler that uses lazy task creation.

Intel® Cilk™ Plus Implementation Experience

- Current features available in Intel® compilers
  - For CPU, Many integrated cores (MIC), and integrated GPU
  - Run-time library is open source
- Partial implementation in GCC – ongoing
- At least three approaches have been used successfully for the work-stealing cactus stack
  - Heap-based (Cilk-5 from MIT, Cilk++ from Cilk Arts)
  - Multiple stacks (Intel® Cilk™ Plus) **Link Compatible!**
  - Per-core memory-mapped stacks (Cilk-M from MIT)
- Specification for Intel® Cilk™ Plus is available at: http://software.intel.com/en-us/articles/intel-cilk-plus-specification/

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- **Conclusion**
  - Known challenges
  - Next Steps
  - References
  - Acknowledgements

Conclusions

“The Free Lunch is Over”

– Herb Sutter

“Parallel programming need not be just a collection of *ad hoc odd hacks*”

– Charles Leiserson

Conclusions

- Programmers will write parallel programs in C++, whether with hacks or non-standard extensions.
- The technologies for parallelization are much more mature than most people realize
  - Vectorization and work-stealing schedulers have been around for decades.
  - This used to be the province of super computers, but today a super computer fits in your pocket!
- Intel® Cilk™ Plus provides a fully-implemented starting point for standardization.

Next Steps

- Intel® Cilk™ Plus will become the basis for a set of proposals for C++ language constructs.
  - We are still evolving Intel Cilk Plus and are open to feedback
- We will not necessarily be proposing the entire Intel® Cilk™ Plus specification as a single proposal
  - Individual features may be proposed separately
  - Some features may evolve before being proposed
  - Some features may not be proposed
- Expect the first proposals at the October C++ Standards Meeting.

References

- Intel® Cilk™ Plus Specification
  http://software.intel.com/en-us/articles/intel-cilk-plus-specification/
- Edward Lee, *The Problem with Threads*
  http://www.eecs.berkeley.edu/Pubs/TechRpts/2006/EECS-2006-1.pdf
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- Mohr et. al., *Lazy Task Creation: A Technique for Increasing the Granularity of Parallel Programs*
  http://dl.acm.org/citation.cfm?id=629042

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  - Charles Leiserson
  - Arch Robison
  - The Cilk Plus runtime team at Intel
  - The Parallel Programming Models Working Group at Intel

Backup Slides

User-defined reducers

```
template <class T> struct multiply_monoid
  : public cilk::monoid_base<T>
{
    void identity(T* p) { ::new(p) T(1); }
    void reduce(T* left, T* right) {
        *left *= *right;
    }
};
...
cilk::reducer<multiply_monoid<double>> product(1.0);
cilk_for (std::size_t i = 0; i < sz; ++i)
    product() *= a[i];
```

Other Types of Hyperobjects

- Holders
  - Work like thread-local storage, but are tied to logical structure of parallel program, not to thread.
  - Can also be used to optimize logically-parallel computations that actually occur serially.
- Splitters
  - Allows parallel strands to read the same value, but keeps modifications separate
  - Implementation techniques are still an area of research

Array Notations → Vector Operations

- Selection of array elements
  - "vector" refers to a 1D array. Current implementation is does not allow [:] to be overloaded, e.g., for std::vector.

```
A[:]       // All of vector A
B[2:6]     // Elements 2 to 7 of vector B
C[:][5]    // Column 5 of matrix C
D[0:3:2]   // Elements 0,2,4 of vector D
```

Known Challenges & Limitations

- Functions that spawn may return on a different thread than they were called on, causing problems with TLS.
- Array notation is currently limited to built-in arrays
  - No overloading for vector<>, array<>, etc.
- Array sections do not participate in the C++ type system; you cannot declare a variable of array-section type.
- #pragma is an ugly syntax for SIMD annotation
- Overlapping (i.e., partially redundant) functionality among array notation, cilk_for, and #pragma SIMD.

Optimization Notice

Optimization Notice

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