C Language Constructs for Parallel Programming

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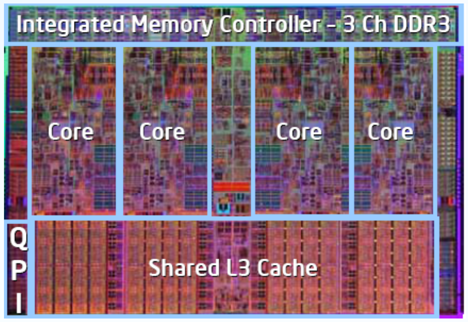
Today's objective

- Present a proposal for addition of language constructs for parallel programming to C
- Get feedback:
  - Is there an interest in adding parallel programming to C?
  - Possible next steps

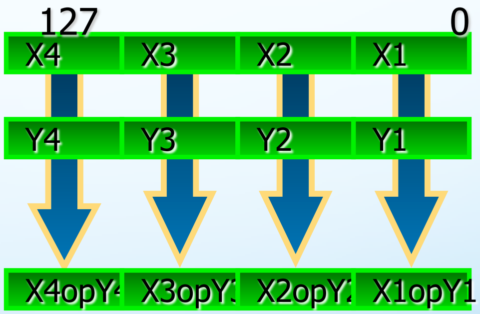
Parallel Programming Required for Current HW

Multiple cores



Tasks

SIMD instructions



Vectors

Array Notation

Vector loops

Why Parallelism?

- Virtually all computers today contain multiple cores and vector instruction sets,
  - Even 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

Why Add Parallelism Constructs to C

- Parallel programming is **Hard!**
- Without standard support, parallel programming often falls back on error-prone, ad-hoc protocols.
- Programming directly with threads often leads to undesirable non-determinism

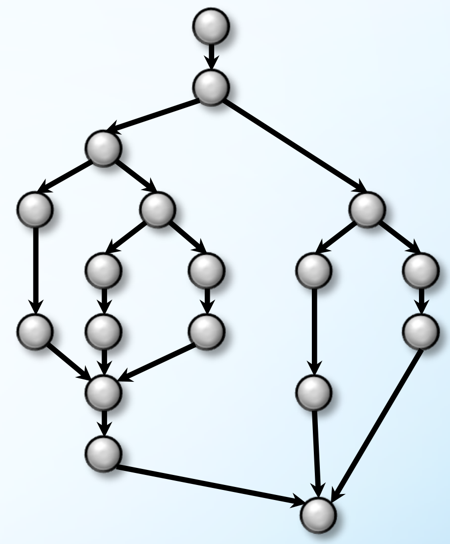
- Treads and locks are not composable: Combining components introduces errors (e.g., deadlocks) or performance problems (e.g., oversubscription).

- C is behind other languages: OpenMP, OpenCL etc

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

Parallelism versus Concurrency

Parallel computing
A form of computing in which computations are broken into many pieces that are executed simultaneously.



Concurrent computing
A form of computing in which computations are designed as collections of interacting processes.

Characteristics of the Proposal

1. Standardize existing practices
   – Codify what users are actually doing

2. Based on existing implementations
   – Intel compiler, GCC, similar concepts in other languages, many years of Cilk research

3. A composable tasking model

4. Parallelism is not mandatory, can be turned off, with serial equivalence

5. Vector programming

Cilk Plus

Parallel tasks	• Easy to learn: 3 keywords • 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 Loops	• Vectorization annotation for loops • Single threaded vector parallelism

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_wak

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

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

Spawning is not Thread Creation

- Spawns and syncs describe the parallel structure of the code.
  - Code is *processor oblivious*: the number of cores is not specified.
  - Expressed parallelism usually exceeds actual parallelism
- A `cilk_spawn` gives the runtime *permission* to continue in parallel.
  - No new threads are created
  - Low cost (5x to 10x cost of a function call)
- A `cilk_sync` is a local synchronization point
  - No global barrier is implied
  - Threads do not stall on a sync.

“Serialization” of Tree-walk Example

```
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;
}
```

Why Work Stealing?

- A work-stealing scheduler can be shown mathematically to be within a factor of 2 of optimal, for a program with sufficient parallelism.
  - In practice, it is usually very close to optimal.
  - 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.

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() execute

The loops has to be a countable loop

Multiple linear increments allowed

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

Reducer Hyperobjects

- "Traditional" reduction on a parallel for loop:

```
long a[sz];
reducer_opadd<int> sum = 0;
cilk_for (int i = 0; i < sz; ++i)
    sum += a[i];
```

Parallel accesses each get their own "view"

- Generalized reduction for any code executing in parallel:

```
reducer_opadd<int> sum = 0;
void sum_tree(node* nodep) {
  if (nodep->left) cilk_spawn sum_tree(nodep->left);
  if (nodep->right) cilk_spawn sum_tree(nodep->right);
  sum  += nodep->value;
}
```

Cilk Plus

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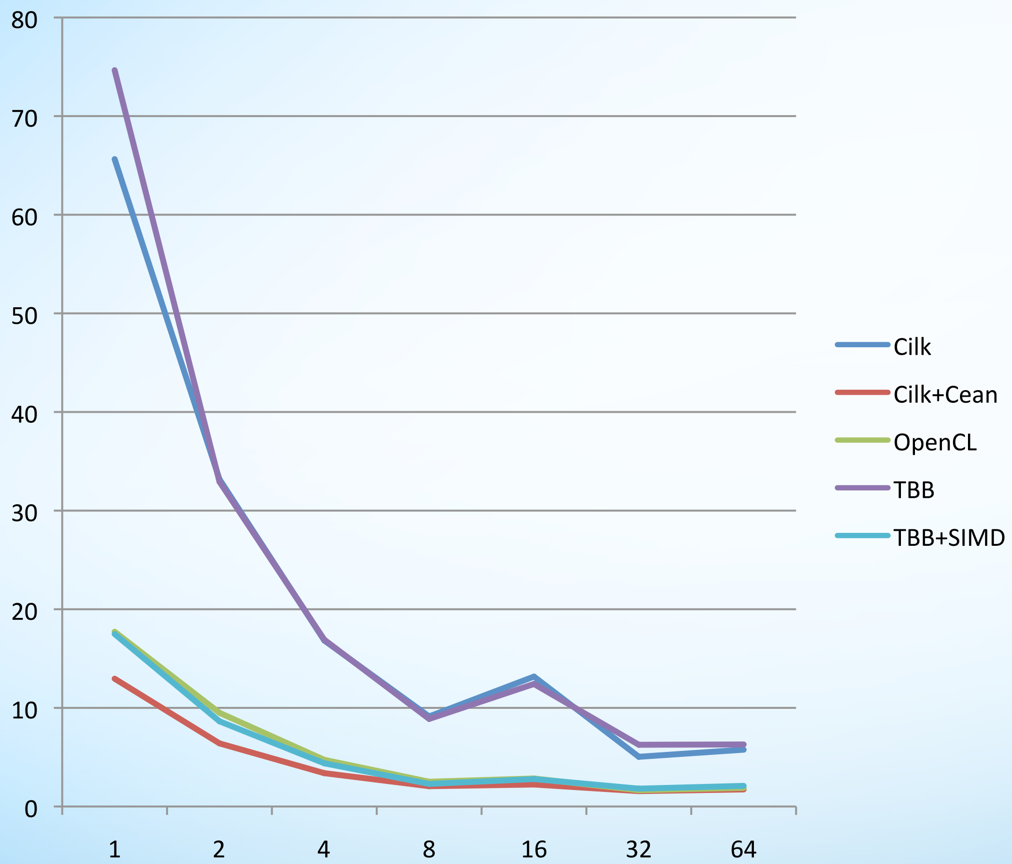
Elemental Functions	• Data-parallel function mapping
SIMD Loops	• Vectorization annotation for loops • Single threaded vector parallelism

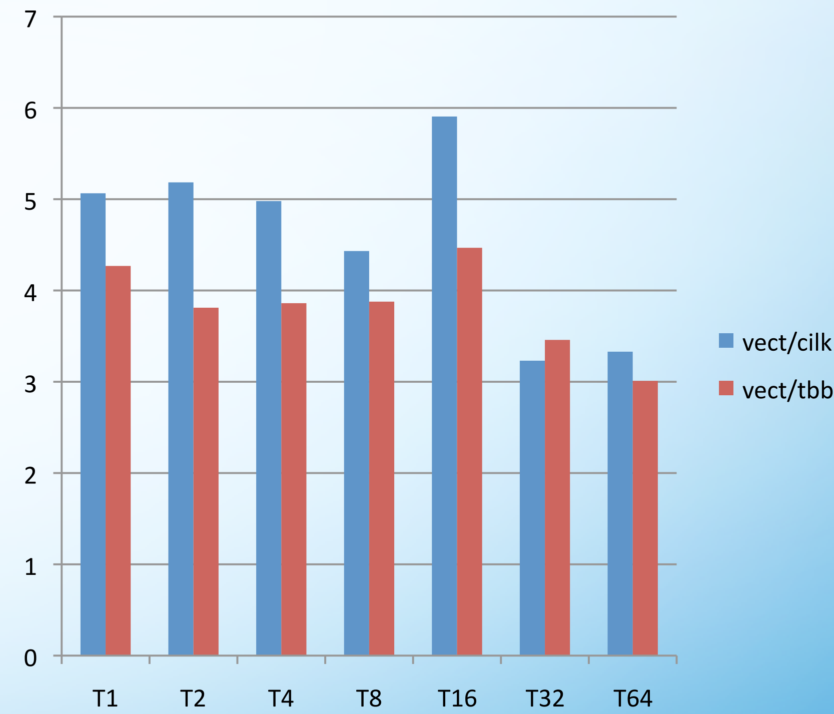
Significance of vectorization - RTM stencil

	1	2	4	8	16	32	64
Cilk	65.64	33.18	16.83	9.13	13.17	5.04	5.76
Cilk+vec	12.96	6.4	3.38	2.06	2.23	1.56	1.73
OpenCL	17.72	9.5	4.73	2.51	2.84	1.65	1.89
TBB	74.66	32.93	16.91	8.88	12.42	6.26	6.29
TBB+ vec	17.49	8.64	4.38	2.29	2.78	1.81	2.09

- In both Cilk+vec and TBB+vec, significant speed up over tasking alone, at all thread counts
- Without vectorizaiton, OpenCL (SPMD model) wins over C/C++

And now with pictures





Optimization Notice

Significance of vectorization – Track Fitting

nthreads	cilk	cilk_simd	opencl	tbb	tbb_simd
1	47.27	24.94	16.96	43.04	22.43
2	24.02	12.79	8.74	20.9	11.49
4	12.38	6.63	4.8	10.7	5.77
8	6.85	3.47	2.85	5.45	2.94
16	6.17	3.21	2.61	5.2	2.71
32	2.48	1.41	1.66	2.02	1.16
64	2.08	1.19	1.56	1.55	0.93

Vector level parallelism provides significant improvement over thread level parallelism

Array Notations

- Concise data-parallel notation encourages effective exploitation of vectors
- 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<size; 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

- An array section doesn't have a new kind of type
  - the type of an array section is exactly that of the analogous subscript expression.
  - Additionally, an array section has rank and shape.
- A section implicitly iterates over some elements of an array.
  - Rank is the number of levels of loop nesting (i.e. dimensions) in the iteration space.
  - Shape is a (mathematical) vector of lengths. (The rank is the same as the length of the shape vector.)

Rank and Shape (continued)

- The rank of an expression is determined statically. In general the shape of a section is determined dynamically.

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

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
```

- Masked vector operations

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

Array x scalar operation

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)
  - 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 can break data into SIMD vectors and call function on each vector

- Invoking the elemental function:

```
// The following loop can also use cilk_for
for (int i=0; i<NUM_OPTIONS; i++)
    call[i] = option_price_call_black_scholes(S[i], K[i], r,
                                              sigma, time[i]);
```

Vector loops

- 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)
{
    simd_for (int i = 0; i < n; ++i)
        a[i] = 2 * b[e[i]];
}
```

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

- The loop has to be countable
- Multiple linear increments allowed
- Semantics: relaxed order of evaluation to allow vectorization
  - But vectorization is not mandatory

Vector Loops vs. Parallel Loops

- Both are countable
- Parallel loops
  - are multi threaded
  - Iterations can execute in any order
  - Admit synchronization (e.g. critical sections)
  - No data dependence
- Vector Loops
  - Are single threaded
  - Allow forward data dependence
  - No synchronization
- Prevalent use case: manage parallelism at the outer level, vectorize at the inner level
  - in a deep loop hierarchy
  - Divide and conquer algorithms

Countable Loops

```
some_for ( init ; compare ; increment-list ) statement
```

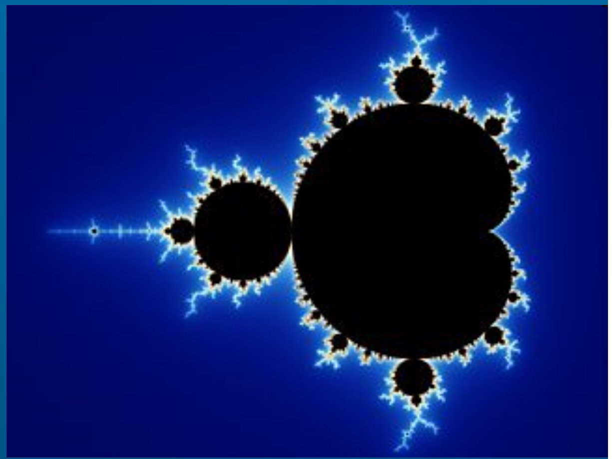
- Init: no restrictions
- Compare: must be present
  - One operand has to be a variable
- Increment-list: at least one increment
  - Increment the variable used in the compare
  - All increments are linear.
- Body: no break, return.

Cilk_for

- A countable loop → efficient scheduling
- Parallelism is allowed, not mandatory
- Same scheduler as cilk_spawn, therefore
  - Same space efficiency guarantees
  - Same serial equivalence guarantees
  - Well defined serial elision
  - Reductions works when operations combine both cilk_for and cilk_spawn
  - The body of the loop is a task block, impact the scope of a *cilk_sync*
- Synchronization (e.g. critical sections) is expected and allowed, and
  - Loops w/o synchronization can also be vectorized
  - When in doubt, the loop cannot be vectorized, <u>even</u> partially.
  - Other compiler loop optimizations apply

Example: Mandelbrot in Cilk

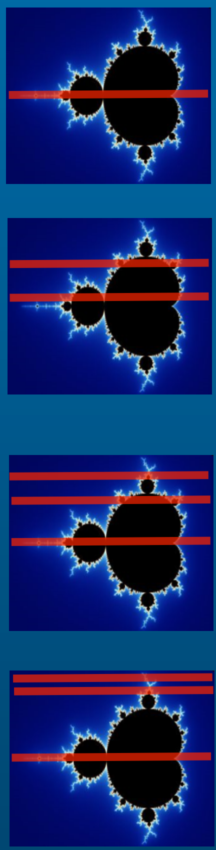
```
int mandel(complex c, int max_count) {
  int count = 0; complex z = 0;
  for (int i = 0; i < max_count; ++i) {
    if (abs(z) >= 2.0) break;
    z = z*z + c; count++;
  }
  return count;
}
```



```
cilk_for (int i = 0; i < max_row; i++){
  for (int j = 0; j < max_col; j++ ) {
    p[i][j] = mandel( complex(scale(i), scale(j)), depth);
  }
}
```

One word change to sequential version
Compiler support hides complexity

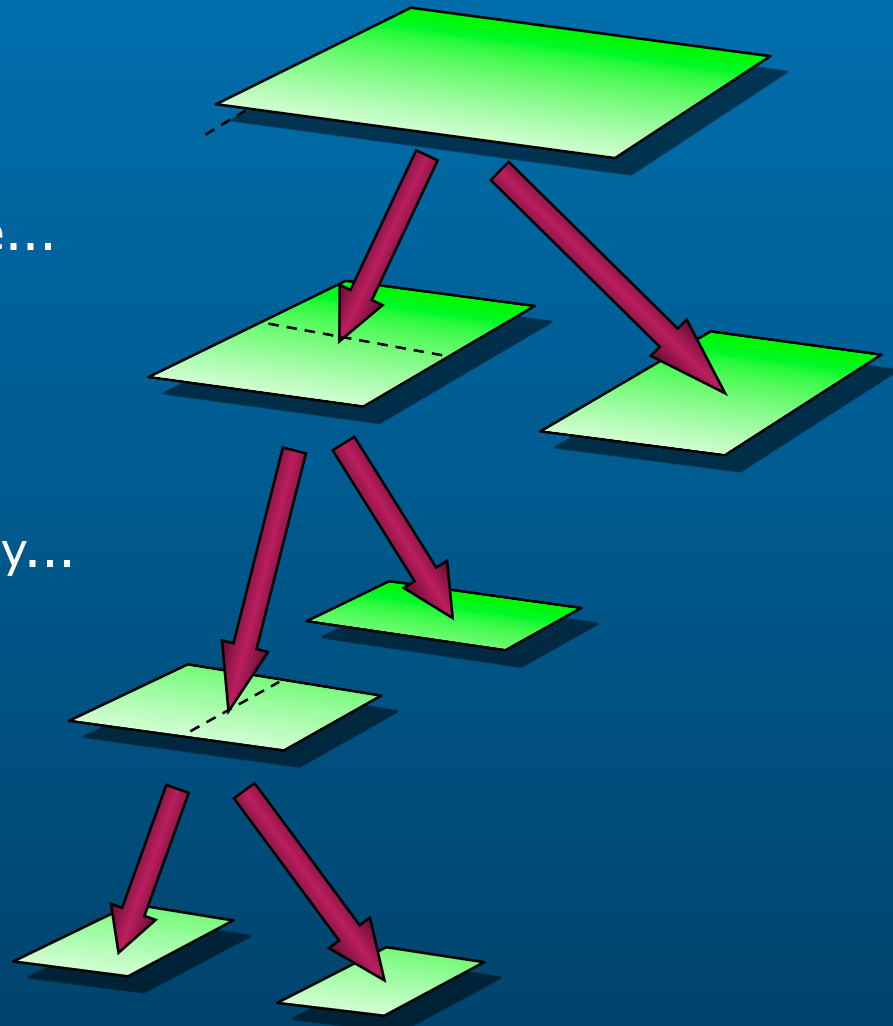
Divide and Conquer Parallelism



Split range...

.. recursively...

...until ≤ grainsize.



cilk_for recursively divides a loop into tasks

Vector loops

- We are not inventing vector execution.
- We are just adding language to express it
- Vector execution is well understood, and customers have clear expectations regarding what they can do.

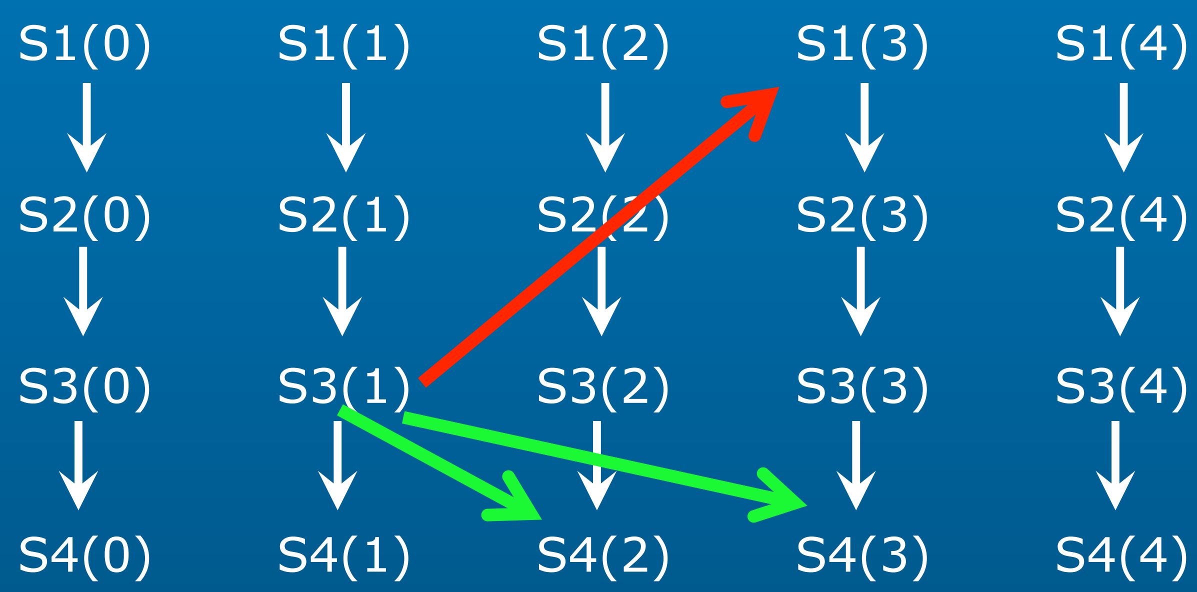
```
simd_for <chunk=N> (init ; compare; increment-list) statement
```

Vector Loops - Expectations

- Any loops in a loop hierarchy can be a vector loop
  - E.g. there can be a loop inside the vector loop
  - But not a parallel loop inside a vector loop
  - The vector loop participates in the compiler's loop hierarchy optimization (blocking, splitting etc)
- The loop is countable, but trip count can be any
  - not specific to size of HW vector registers
  - The compiler is responsible for <u>peeling</u> (alignment) and <u>remainder</u>
- Functions can be called from the vector loop, execute efficiently
  - E.g. sin(), exp()
- Data alignment is not necessarily known in the lexical scope of the vector loop
- Can mix scalar and vector operations on the same data
- Some (forward) data dependence patters are expected
- Therefore: single threaded execution expected
  - Both for semantics and performance model
- Results should be the same as if the loop was not vectorized
  - Some programmers do deviate on this expectation.

This proposal attempts to capture existing expectations, not to invent something completely new.

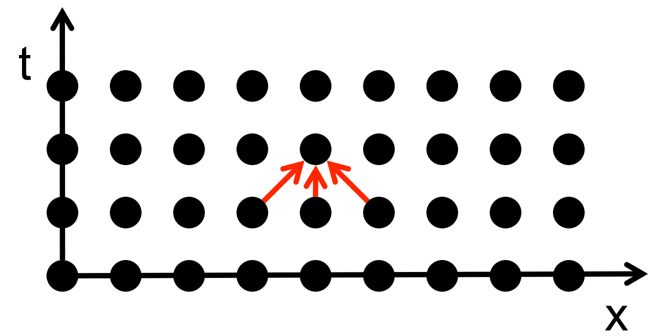
```
simd_for (i=0; i<n; i++) {
  S1;
  S2;
  S3;
  S4;
}
```

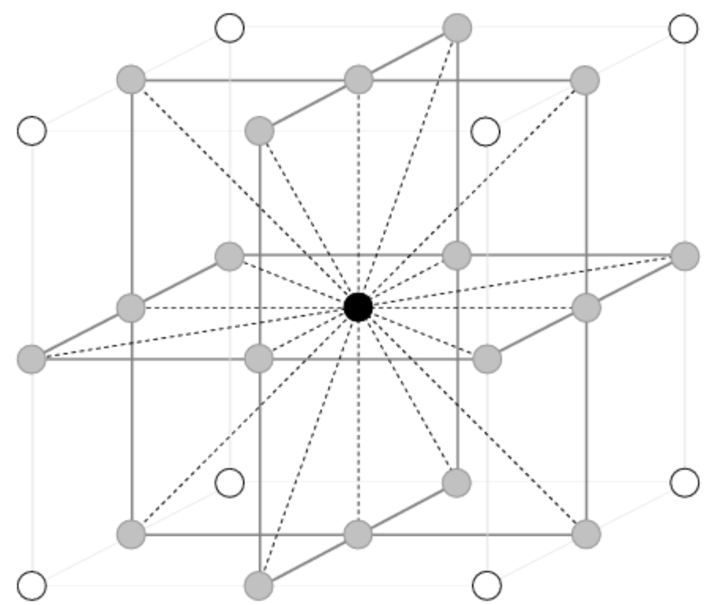


- Parallel execution
  - No colored dependences allowed
- Vector execution
  - Red dependence not allowed (backward)
  - Green dependence allowed (forward)
  - Refinement with explicit chunk size
    - Red dependence allowed if dependence distance is >= chunk

Stencils

- For a given point, a *stencil* is a fixed subset of nearby neighbors.
- A *stencil code* updates every point in an d-dimensional spatial grid at time t as a function of nearby grid points at times t–1, t–2, …, t–k.
- Stencils are used in iterative PDE solvers such as Jacobi, multigrid, and AMR, as well as for image processing and geometric modeling.





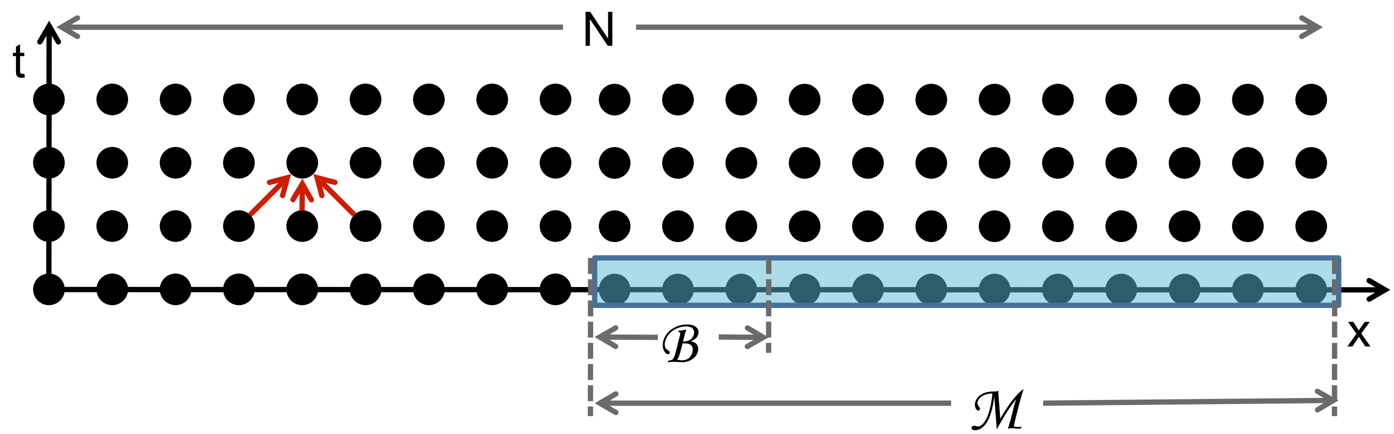
Looping Implementation

A nested loop implementation is straightforward:

```
for (t = 1; t≤T, ++t) {
  for (i0 = 0, i0<n0, ++i0) {
    for (i1 = 0, i1<n1, ++i1) {
      for (i2 = 0, i2<n2, ++i2) {
        ⟨⟨ update A[t%k,i0,i1,i2] according to stencil ⟩⟩
} } } }
```

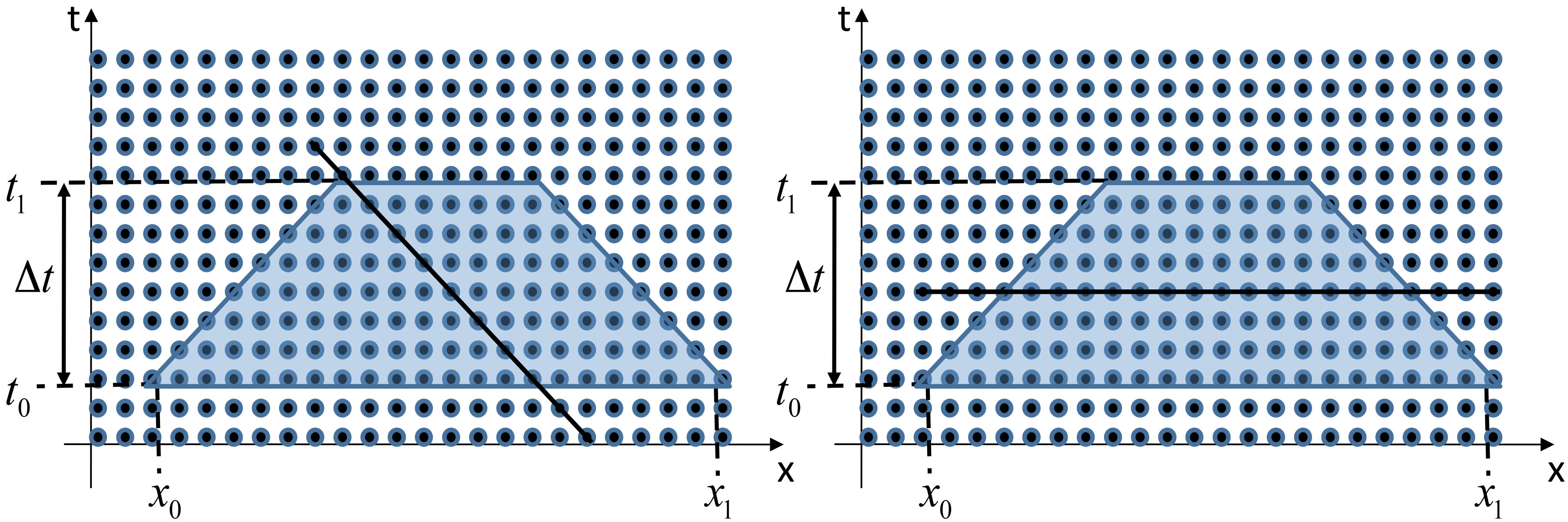
Conventional Optimization: Loop Tiling

Issues in Looping Implementation



Issue: Looping is memory intensive, especially for parallel implementations, and it uses caches poorly. Assuming data-set size N, cache-block size $\mathcal{B}$, cache size $\mathcal{M} <$ N, the number of cache misses is $\Theta(N/\mathcal{B})$.

Cache-Oblivious Algorithms



Divide-and-conquer cache-oblivious techniques, based on *trapezoidal decompositions* are known to be effective.

DnC is a recursive algorithm that cuts the grid

The recursion is parallelized

The base case is the original loop.

It should also be vectorized. It cannot be a parallel loop.

No 1:1 correspondence between source code and vector code

```
int A[1000]; double B[1000];
void foo(int n){
 int i;
 simd_for (i=0; i<n; i++){
  B[i] += ABS(A[i]);
 }
}
```

-SSE2

```
movq      xmm1, [A+r9+rax*4]
pxor      xmm0, xmm0
pcmpgtd   xmm0, xmm1
pxor      xmm1, xmm0
psubd     xmm1, xmm0
cvtdq2pd  xmm2, xmm1
addpd     xmm2, [B+r9+rax*8]
movaps    [B+r9+rax*8], xmm2
add       rax, 2
cmp       rax, rcx
jb        .B1.4
```

ABS sequence

2 elements

AVX

```
vpabsd    xmm0, [A+r9+rax*4]
vcvtdq2pd ymm1, xmm0
vaddpd    ymm2, ymm1, [B+r9+rax*8]
vmovupd   [B+r9+rax*8], ymm2
add       rax, 4
cmp       rax, rcx
jb        .B1.4
```

4 elements

SSSE3

```
movq      xmm0, [A+r9+rax*4]
pabsd     xmm1, xmm0
cvtdq2pd  xmm2, xmm1
addpd     xmm2, [B+r9+rax*8]
movaps    [B+r9+rax*8], xmm2
add       rax, 2
cmp       rax, rcx
jb        .B1.4
```

ABS instruction

2 elements

Outer Loop Example: Mandelbrot

```
simd_for (i=0; i<n; i++) {
    complex<float> c = a[i];
    complex<float> z = c;
    int k = 0;
    while ((k < max_cnt)
          && (abs(z)< limit)) {
          z = z*z + c;
          k++;
    };
    color[i] = k;
}
```

An outer loop can also be a vector loop.
This one has a while loop inside.
It means that each “vector lane”
executes the inner while loop.

Cilk™ Plus Implementation Experience

- Current features available in Intel compiler
  - For CPU, Many integrated cores (MIC), and integrated GPU
  - Run-time library is open source
- Partial implementation in Gnu compiler – 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)
  - 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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