Cilk Plus: Language Support for Thread and Vector Parallelism

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Outline

Motivation for Intel® Cilk™ Plus

SIMD notations

Fork-Join notations

Karatsuba multiplication example

GCC branch

Multi-Threading and Vectorization are Essential to Performance

Latest Intel® Xeon® chip:

8 cores
× 2 independent threads per core
× 8-lane (single prec.) vector unit per thread

= 128-fold potential for single socket

Intel® Many Integrated Core Architecture

>50 cores (KNC)
× ? independent threads per core
× 16-lane (single prec.) vector unit per thread

= parallel heaven

Importance of Abstraction

Software outlives hardware.

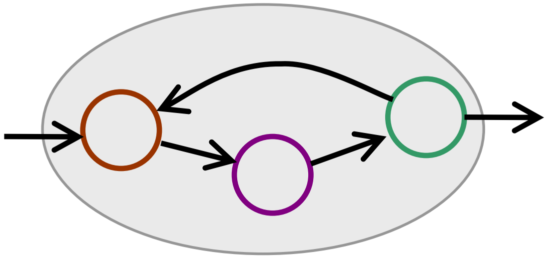
Recompiling is easier than rewriting.

Coding too closely to hardware du jour makes moving to new hardware expensive.

C++ philosophy: abstraction with minimal penalty

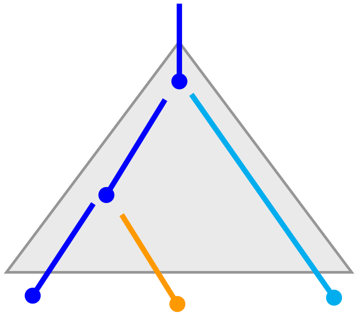
Do not expect compiler to be clever.
But let it do tedious bookkeeping.

"Three Layer Cake" Abstraction



Message Passing

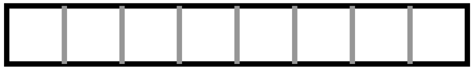
exploit multiple nodes



Fork-Join

exploit multiple cores

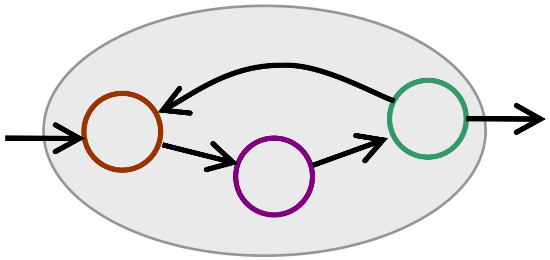
exploit parallelism at multiple algorithmic levels



SIMD

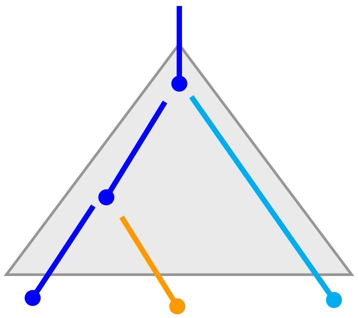
exploit vector hardware

Composition



Message Driven

compose via send/receive



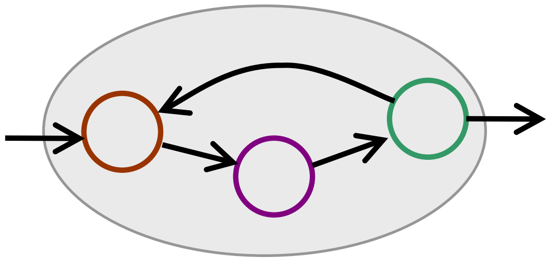
Fork-Join

compose via call/return

SIMD

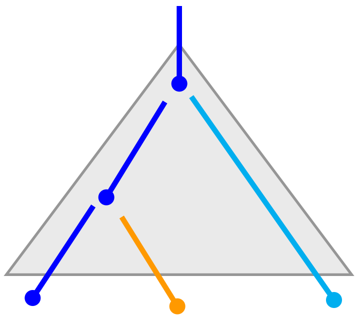
compose sequentially

Implementing the Cake



Message Driven

MPI, tbb::flow



Fork-Join

OpenMP, TBB, or Cilk

Intel® Cilk™ Plus

SIMD

Array Notation or #pragma SIMD

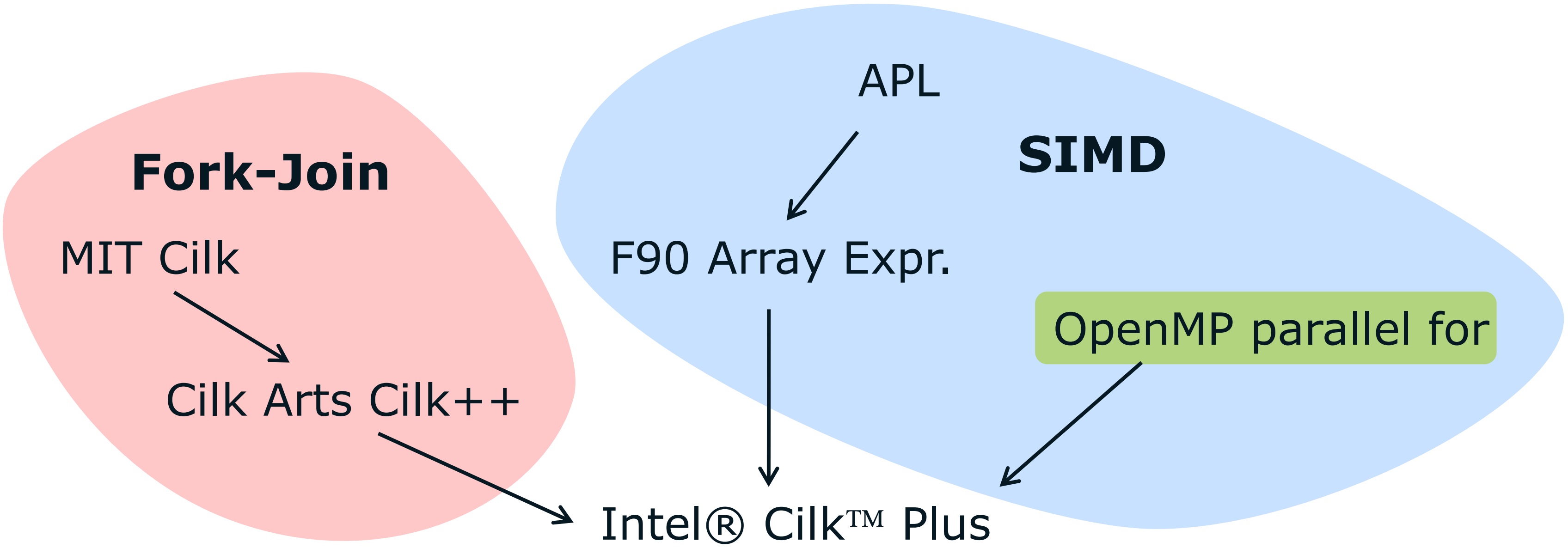
Optimization Notice

Intel® Cilk™ Plus

Introduced in 2010 by Intel 12.0 compiler

Open specification

Covers both fork-join and SIMD



Optimization Notice

Background

Vectorization of C/C++ is hard...

```
void saxpy( float a, float x[], float y[], size_t n ) {
    for( size_t i=0; i<n; ++i )
        y[i] += a*x[i];
}
```

... because aliasing is allowed!

```
// Set z to frequencies of piano keys
float z[88];
std::fill_n( z, 88, 0 );
z[0] = 27.5;
saxpy( 1.059463f, z, z+1, 87 );
```

SSE intrinsics freeze vector length.

Painful to write.

SSE Intrinsics

_mm_add_ps,
_mm_sub_ps,
_mm_mul_ps,
...

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] += a*x[0:n];
}
```

Array Section Notation

Pointer or array.

base[*first*:*length*:*stride*]

First index

Number of elements (different than F90!)

Optional stride

Rules for *section*$_1$ *op* *section*$_2$

- Elementwise application of *op*
- Also works for *func*(*section*$_1$, *section*$_2$)
- Sections must be the same length
- Scalar arguments implicitly extended

More Examples

- Rank 2 Example – 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]);
```

Scalar implicitly extended

- 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];
```

Improvement on Fortran 90

Compiler does *not* generate temporary arrays.

- Would cause unpredictable space demands and performance issues.
- Want abstraction with minimal penalty.
- Partial overlap of left and right sides is undefined.

Exact overlap still allowed for updates.

- Just like for structures in C/C++.

```
x[0:n] = 2*x[1:n];          // Undefined – partial overlap*
x[0:n] = 2*x[0:n];          // Okay – exact overlap
x[0:n:2] = 2*x[1:n:2];      // Okay – interleaved
```

*unless n≤1.

Optimization Notice

Reductions

Build-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] );
}
```

sum reduction

elementwise multiplication

#pragma simd

Another way to grant permission to vectorize.

- Programmer responsible for correct use.
- Ignorable by compilers that do not understand it.
- Similar in style to OpenMP "**`#pragma parallel for`**"

```
void saxpy( float a, float x[], float y[], size_t n ) {
#pragma simd
    for( size_t i=0; i<n; ++i )
        y[i] += a*x[i];
}
```

Clauses for Trickier Cases

`linear` clause for induction variables

`reduction` clause for reduction variables

`private`, **`firstprivate`**, **`lastprivate`** à la OpenMP

```
float dot( float *x, float *y, size_t n ) {
    float sum = 0;
#pragma simd linear(x,y), reduction(+:sum)
    for( size_t i=0; i<n; ++i )
        sum += (*x++) * (*y++);
    return sum;
}
```

Conditionals/Masking

Array sections can be used to control "if":

```
if( a[0:n] < b[0:n] )
    c[0:n] += 1;
```

- Can use **`#pragma simd`** on loops with conditionals

```
#pragma simd
for( int i=0; i<n; ++i )
    if( a[i]<b[i] )
        c[i] += 1;
```

Elemental Functions

Enables vectorization of separately compiled scalar callee.

In file with definition.

```
__declspec(vector)
float add(float x, float y) {
    return x + y;
}
```

In file with call site.

```
__declspec(vector) float add(float x, float y);

void saxpy( float a, float x[], float y[], size_t n ) {
#pragma simd
    for( size_t i=0; i<n; ++i )
        y[i] = add(y[i], a*x[i]);
}
```

Final Comment on Array Notation and `#pragma SIMD`.

No magic – just does tedious bookkeeping.

Use “structure of array” (SoA) instead of “array of structure” (AoS) to get SIMD benefit.

Cilk for Fork-Join Parallelism

Cilk is result of ~15 years of MIT research

- Extension to C/C++

Three keywords

- **cilk_for**
- **cilk_spawn**
- **cilk_join**

Reducers for reductions.

Why Yet Another Idiom for Thread Parallelism?

Simple for non-experts

Predictable performance and space demands

Automatic load balancing

Efficient nested parallelism

Parallel Loops

```
cilk_for( size_t i=1; i<n; ++i )
    DoBorder(i);
cilk_for( size_t i=0; i<n; ++i )
    DoInterior(i);
```

Rules for loop test and increment are similar to OpenMP.
Implementation is radically different.

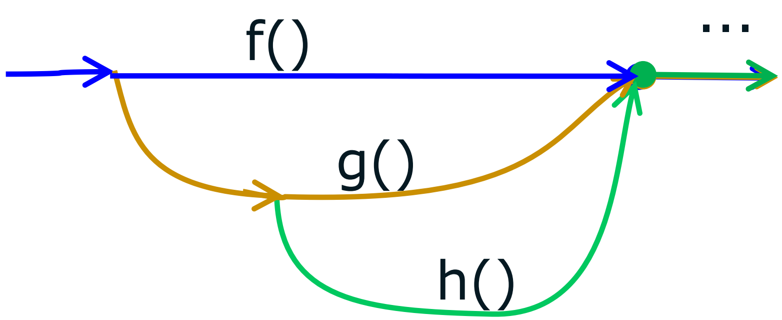
Fork-Join

cilk_spawn makes a call asynchronous

- Caller does not have to wait for callee to return.
- But only if idle processor is available.

cilk_sync waits for spawned calls to complete.

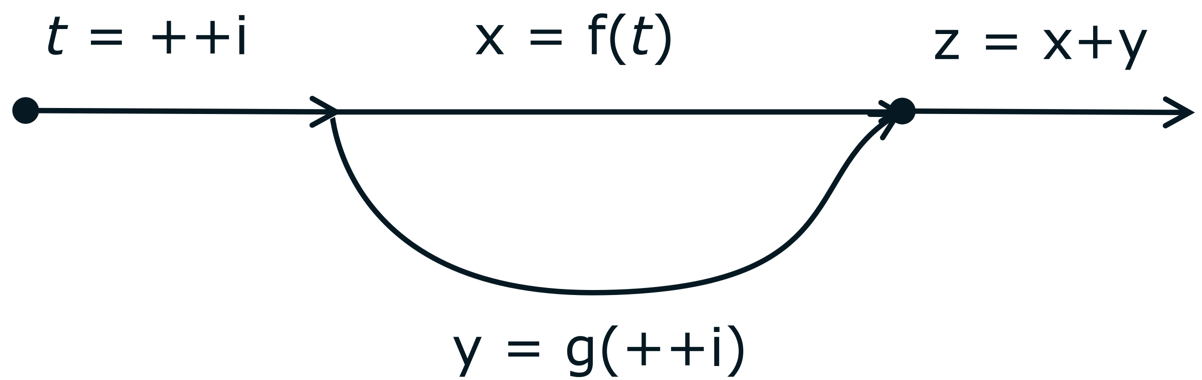
```
cilk_spawn f();
cilk_spawn g();
h();
cilk_sync;
...
```



Argument/Result for Spawned Function

cilk_spawn forks *after* evaluating arguments.

```
x = cilk_spawn f(++i);
y = g(++i);
cilk_sync;
z = x+y;
```



cilk_sync Has Function Scope

Scope of **cilk_sync** is entire function.

End of function has implicit **cilk_sync**.

```
void bar() {
    for( int i=0; i<3; ++i ) {
        cilk_spawn f(i);
        if( i&1 ) cilk_sync;
    }
    // implicit cilk_sync
}
```

Serial call/return property
All Cilk Plus parallelism created in function completes before it returns.

Reducers

Race-free shared global variables without locks!

- Work for any associative reduction operation.
- Work for fork-join, not just loops.

```
cilk::reducer_string r;

void f( const string& s ) {
   r += s;
}
```

```
cilk_spawn f("ABC");
f("DEF");
cilk_sync;
cout << r.get_value() << endl;
```

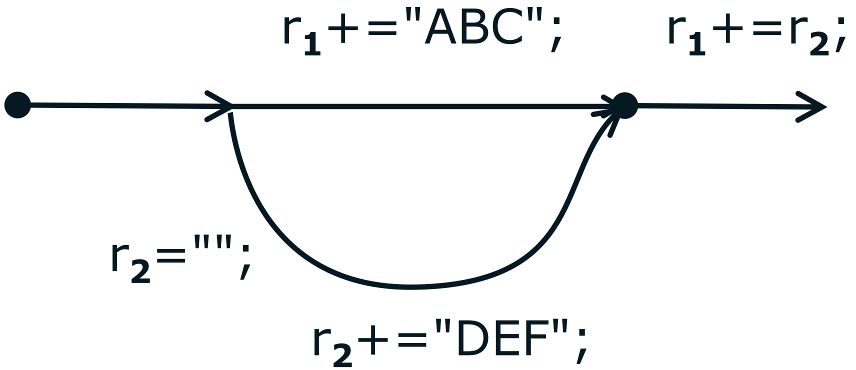

Optimization Notice

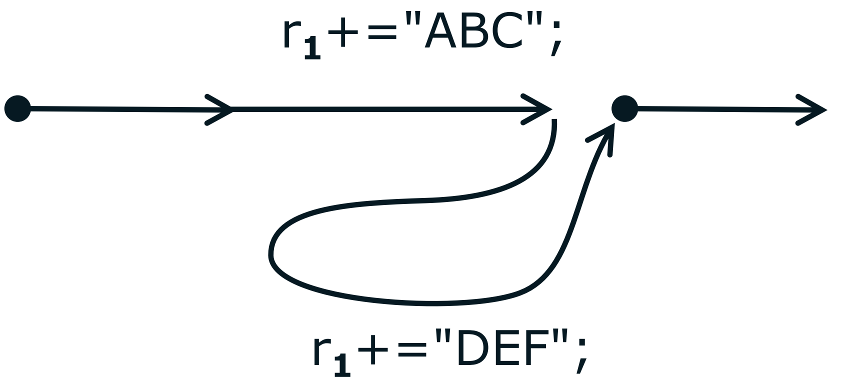
How Reducers Work

```
cilk::reducer_string r;

void f( const string& s ) {
    r += s;
}
```

```
cilk_spawn f("ABC");
f("DEF");
cilk_sync;
cout << r.get_value() << endl;
```



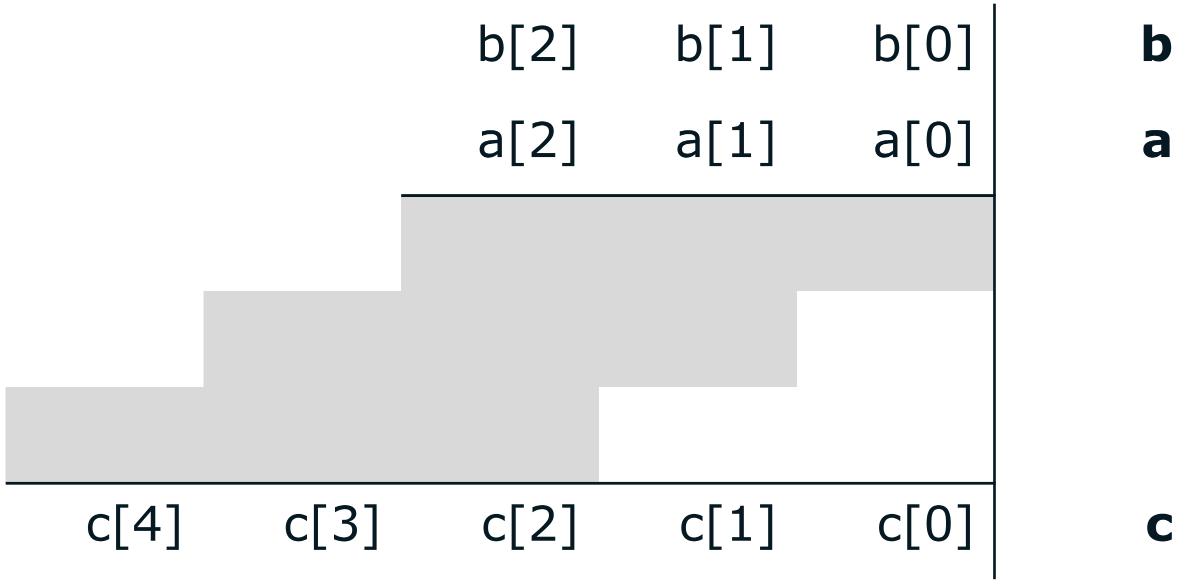


Polynomial Multiplication

Example: $c = a \cdot b$

		x^2 +	$2x$ +	3		**b**
		x^2 +	$4x$ +	5		**a**
		$5x^2$ +	$10x$ +	15		
	$4x^3$ +	$8x^2$ +	$12x$			
x^4 +	$2x^3$ +	$3x^2$				
x^4 +	$6x^3$ +	$16x^2$ +	$22x$ +	15		**c**

Storage Scheme for Coefficients



Karatsuba Trick: Divide and Conquer

Suppose polynomials a and b have degree n

- let $K=x^{\lfloor n/2 \rfloor}$

$$a = a_1 K + a_0$$
$$b = b_1 K + b_0$$

Partition coefficients.

Compute:

$$t_0 = a_0 \cdot b_0$$
$$t_1 = (a_0+a_1)\cdot(b_0+b_1)$$
$$t_2 = a_1 \cdot b_1$$

3 half-sized multiplications.
Do recursively in parallel.

Then

$$a \cdot b \equiv t_2 K^2 + (t_1 - t_0 - t_2)K + t_0$$

Sum products, shifted by multiples of K.

Multithreaded Karatsuba in Cilk Plus

```
void karatsuba( T c[], const T a[], const T b[], size_t n ) {
    if( n<=CutOff ) {
        simple_mul( c, a, b, n );
    } else {
        size_t m = n/2;
        cilk_spawn karatsuba( c, a, b, m );                  // t0 = a0×b0
        cilk_spawn karatsuba( c+2*m, a+m, b+m, n-m );        // t2 = a1×b1
        temp_space<T> s(4*(n-m));
        T *a_=s.data(), *b_=a_+(n-m), *t=b_+(n-m);
        a_[0:m] = a[0:m]+a[m:m];                             // a_ = (a0+a1)
        b_[0:m] = b[0:m]+b[m:m];                             // b_ = (b0+b1)
        karatsuba( t, a_, b_, n-m );                         // t1 = (a0+a1)×(b0+b1)
        cilk_sync;
        t[0:2*m-1] -= c[0:2*m-1] + c[2*m:2*m-1];             // t = t1-t0-t2
        c[2*m-1] = 0;
        c[m:2*m-1] += t[0:2*m-1];                            // c = t2K^2+(t1-t0-t2)K+t0
    }
}
```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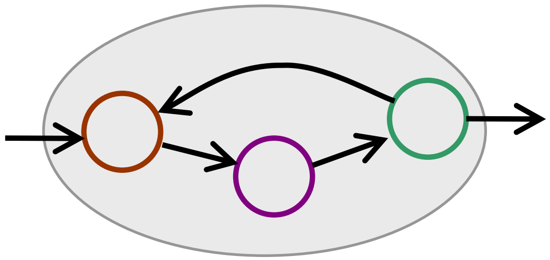
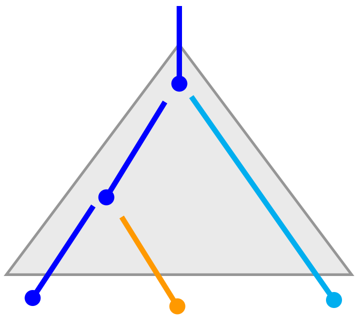
Recap – Three Layer Cake



Message Driven

MPI, tbb::flow



Fork-Join

OpenMP, TBB, or Cilk

Intel® Cilk™ Plus

SIMD

Array Notation or #pragma SIMD

GCC Port

Experimental branch of GCC 4.7

- Implements Cilk Plus specification
- Balaji V. Iyer
- We welcome contributions.

Summary

Intel® Cilk™ Plus abstracts SIMD and thread parallelism.

- SIMD portion works well with OpenMP too.

Parallel programming for non-experts.

- Simple composition rules enable building software from components.

Open specification of language *and* ABI

- GCC experimental branch.
- Ask your compiler vendor to implement it.

Optimization Notice

URLs

Cilk Plus Forum

- http://software.intel.com/en-us/forums/intel-cilk-plus/

Cilk Plus Specifications

- http://software.intel.com/en-us/articles/intel-cilk-plus-specification/

Intel® Cilk™ Plus Software Development Kit

- http://software.intel.com/en-us/articles/intel-cilk-plus-software-development-kit/
  - Cilk Screen Race Detector
  - Cilk View Scalability Analyzer

GCC 4.7 Branch

- http://gcc.gnu.org/svn/gcc/branches/cilkplus/

"Three Layer Cake for Shared-Memory Programming"

- http://portal.acm.org/citation.cfm?id=1953616

Danke!

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