An Interactive Approach to Parallelism

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UPCRC Seminar – Oct 7th

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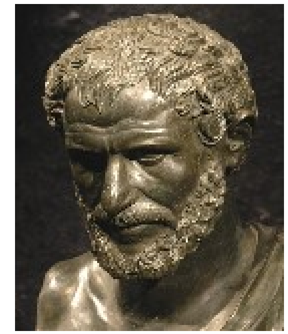
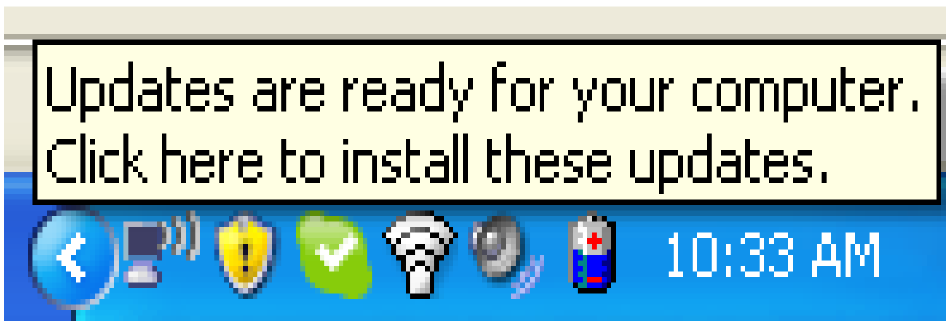
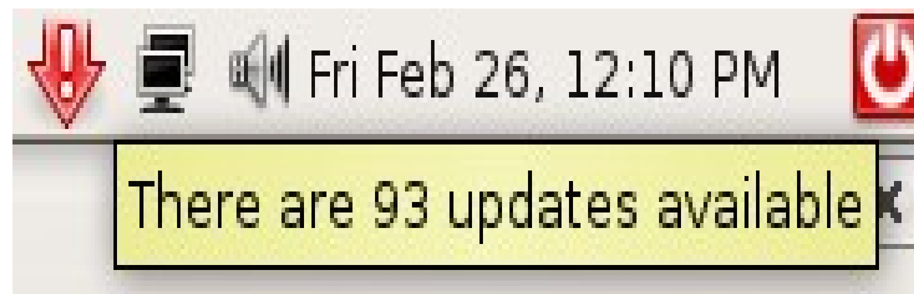
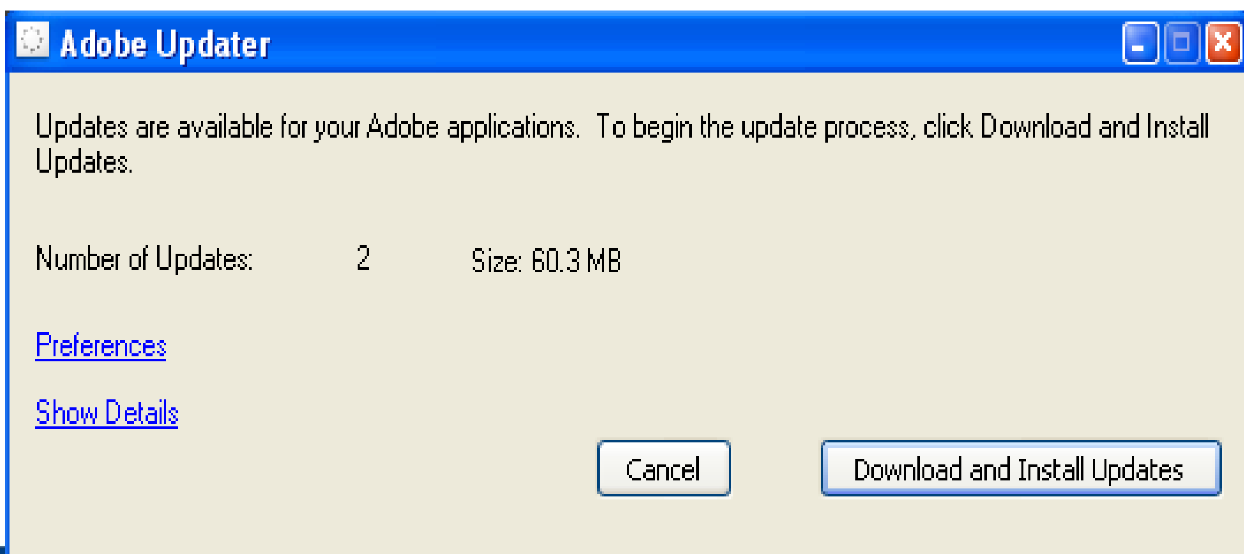
Programming is Program Transformation

"Change is the only guaranteed constant"

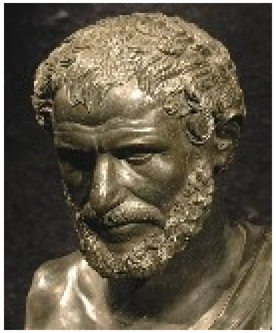








Programming is Program Transformation



"Change is the only guaranteed constant"

Successful software undergoes constant change:

- add more features, fix bugs, improve performance

Programming is about change, and we need to change the way we program to better support change

Q1. What are the changes that occur most often in practice?

Q2. How can we automate them to improve programmer's productivity and software quality?

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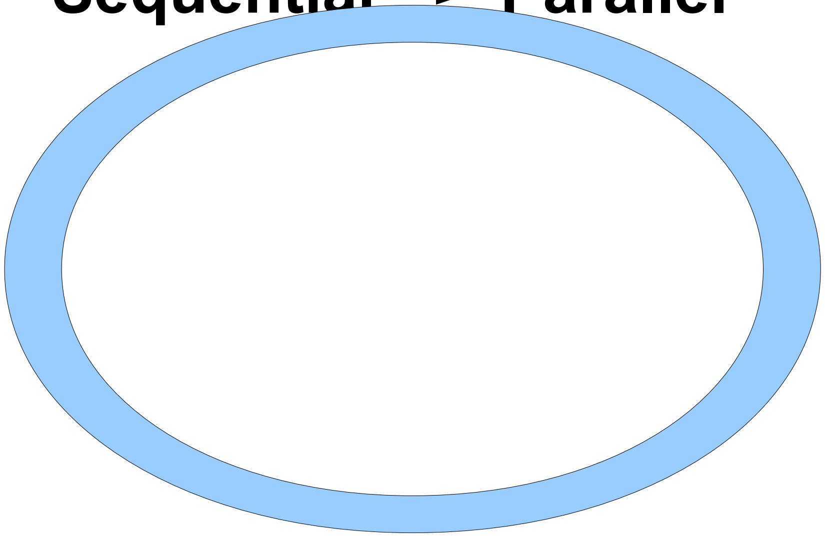
Overview of My Research on Automated Program Transformations

Sequential → Parallel

OOPSLA'09
ASE'09a
ICSE'09



Software Upgrading

ICSE'08
TSE'08
ICSE'07
ECOOP'06
JSME'06
ICSM'05

Software Testing

TSE'10
ASE'09b
ISSTA'08
FSE'07

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Impact of My Tools for Automated Program Transformations

Sequential → Parallel

Concurrencer [ICSE'09] ongoing into Eclipse

Software Upgrading

RefactoringCrawler[ECOOP'06] used at dozens research & industry

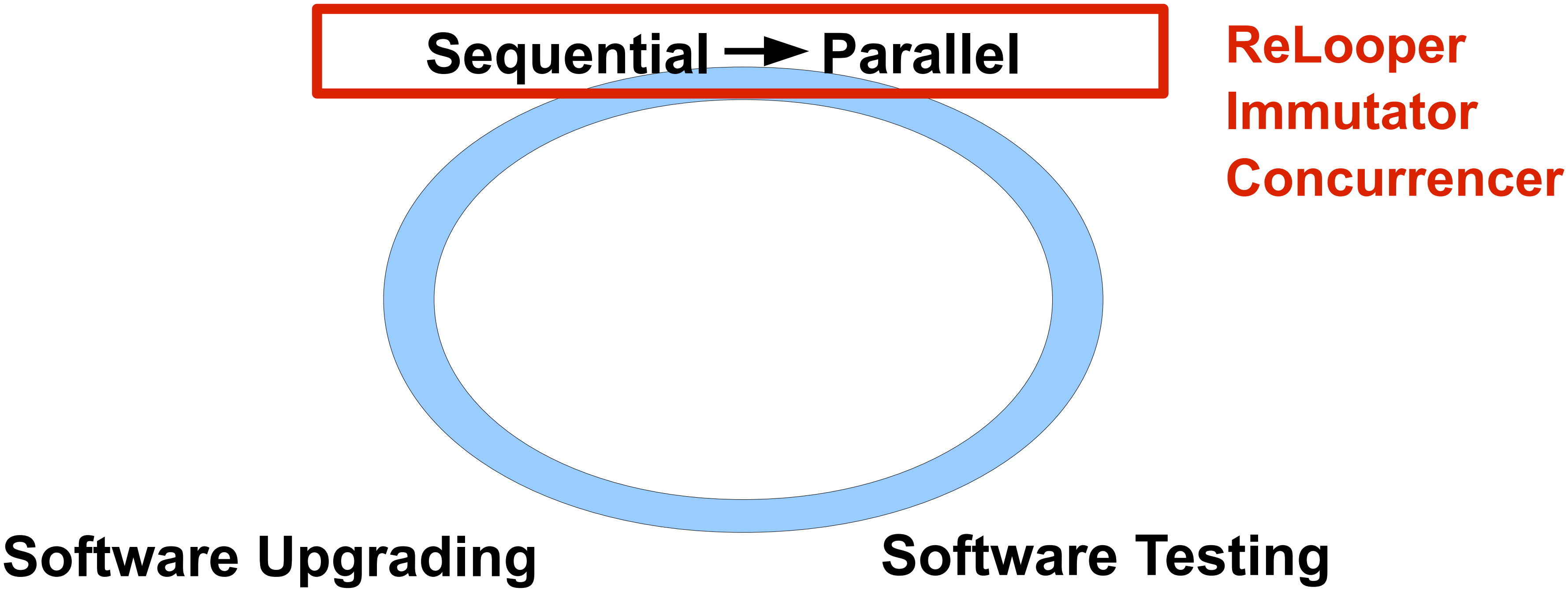
Software Testing

ASTGen [FSE'07] – in the testing infrastructure at Sun NetBeans

Ship with official Eclipse:
- **migrating Java 1.4 to 1.5**
- **record and replay of refactorings**

JavaRefactor (for Jedit): 17,000 downloads

Today's Talk


Sequential → Parallel
ReLooper
Immutator
Concurrencer
Software Upgrading
Software Testing

The Shift to Multicores Demands Work from Programmers

Increased transistor count will be used in coming years to put more cores on a chip

Use parallelism for performance or to enable new applications and services (better QoS, user experience)

Programmers must find and exploit parallelism

A major programming task:

retrofit sequential apps for parallelism

Cannot extract parallelism without user support

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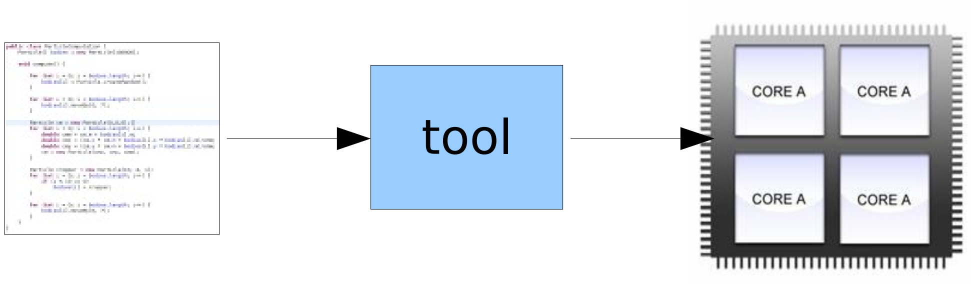
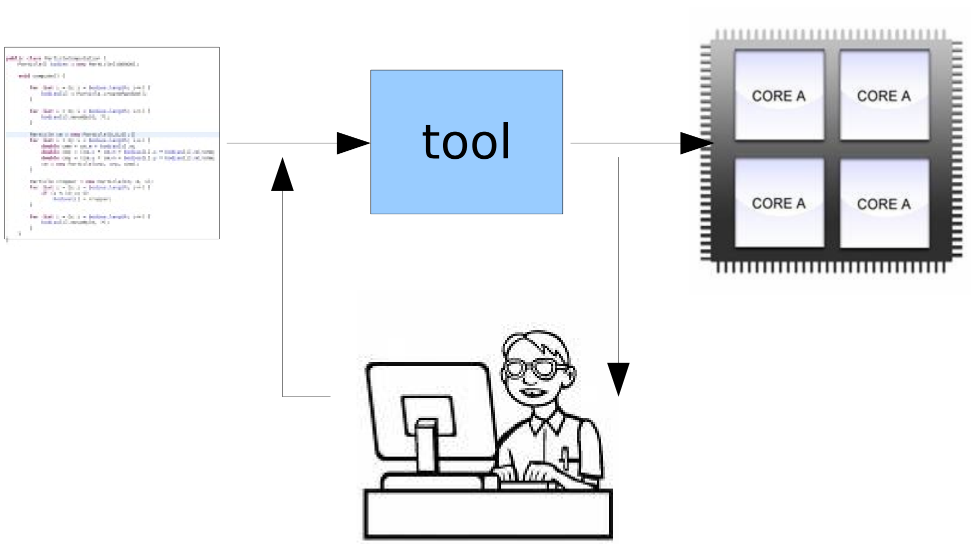
Fully Automatic vs. Interactive Parallelization



Good at fine-grained parallelizing (mostly dense-matrix)
- clueless at coarse-grained parallelism



Benefits:

- **programmer has domain knowledge**
- **combine strengths of programmer and tool (search, remember, compute)**

Challenges:

- **efficient (keep programmer engaged)**
- **handle complex general-purpose programs**

Programmer + Tool >> Tool

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Outline

ReLooper: Refactoring to Loop Parallelism

- Transformations to introduce ParallelArray
- Safety analysis
- Evaluation

Immutator: Convert Mutable into Immutable Class

Future Work

Joint work:
C. Radoi,
M. Tarce,
M. Minea,
R. Johnson

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Hasn't Loop Parallelism Been Solved a Long Time Ago?

	Numerical	Business Apps
Interactive	**Scientific Fortran** Parascope Editor [Kennedy et al.'93], Tiny [Wolfe'91], Sigmacs [Shei and Ganon'90] PAT [Smith and Appelbe'88],	**ReLooper**
Fully Automatic	**Intel's ICC/ICPC** **Fortran Parallelizing Compilers** SUIF [Lam et al. '93] PFC [Kennedy et al. '87], Ptran [Allen et al.'87], Parafrase [Kuck et al.'81]	**Shape Analysis** [Berdine et al.'07, Marron et al.'08] **Points-to Analysis** [Cheng et al.'00, Wu et al.'02] **Memory annotations** [Bocchino et al. '09, Hummel et al.'94, Choi et al.'93, Horwitz et al.'89]

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Anatomy of Loops in Numerical Apps vs. OO Business Apps

	Numerical App	OO Business App
Array element	scalar	Heap-allocated objects, with fields to other objects
Array dimension	multi-dimensional	1-dimension
Loop nestedness	nested	single
Access per iteration	a[i], a[i-n], a[i+n]	a[i]
Analysis question	Do a[i] and a[j] refer same element (does i == j)	Can program reach the same memory location following references through fields?

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A Mutable Particle

```
class Particle {
    double x, y, m;

    public Particle(double x, double y, double m) {
        this.x = x;
        this.y = y;
        this.m = m;
    }

    static Particle createRandom() {
        return new Particle(Math.random(), Math.random(),
                                      Math.random() * 100);
    }

    void moveBy(double dx, double dy) {
        this.x = x + dx;
        this.y = y + dy;
    }
}
```

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A Client Class Working with Particles

```
class ParticleComputation {
  Particle[] bodies;

  void compute() {
    bodies = new Particle[10000000];

    for (int i = 0; i < bodies.length; i++) {
      bodies[i] = Particle.createRandom();
    }

   for (int i = 0; i < bodies.length; i++) {
      bodies[i].moveBy(1, 7);
   }

   Particle cm = new Particle(0,0,0);
   for (int i = 0; i < bodies.length; i++) {
     double cmm = cm.m + bodies[i].m;
     double cmx = (cm.x * cm.m + bodies[i].x * bodies[i].m)/cmm;
     double cmy = (cm.y * cm.m + bodies[i].y * bodies[i].m)/cmm;
     cm = new Particle(cmx, cmy, cmm);
   }
  }
}
```

```
brodman@adama:~/danny$ icpc -O3 Particle.cpp -parallel -par-report3
   procedure: main
   procedure: main
   procedure: compute
   procedure: compute
Particle.cpp(32): (col. 3) remark: loop was not parallelized: existence of parallel dependence.
Particle.cpp(33): (col. 17) remark: parallel dependence: assumed OUTPUT dependence between (unknown) line 33 and (unknown) line 33.
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Particle.cpp(36): (col. 3) remark: loop was not parallelized: existence of parallel dependence.
Particle.cpp(37): (col. 16) remark: parallel dependence: assumed ANTI dependence between this line 37 and this line 37.
Particle.cpp(37): (col. 16) remark: parallel dependence: assumed FLOW dependence between this line 37 and this line 37.
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Particle.cpp(37): (col. 16) remark: parallel dependence: assumed OUTPUT dependence between this line 37 and this line 37.
```

non-interactive

interactive

Changes to be performed

- ☑ ParticleComputation.java - TestProject/src/parallelArray
  - ☑ Update imports
  - ☑ ParticleComputation
    - ☑ Change declaration type
    - ☑ compute()
      - ☑ Replace array assignment
      - ☑ Replace sequential loop with parallel operation: replaceWithGeneratedValue
      - ☑ Replace sequential loop with parallel operation: apply
      - ☑ Replace sequential loop with parallel operation: reduce

ParticleComputation.java

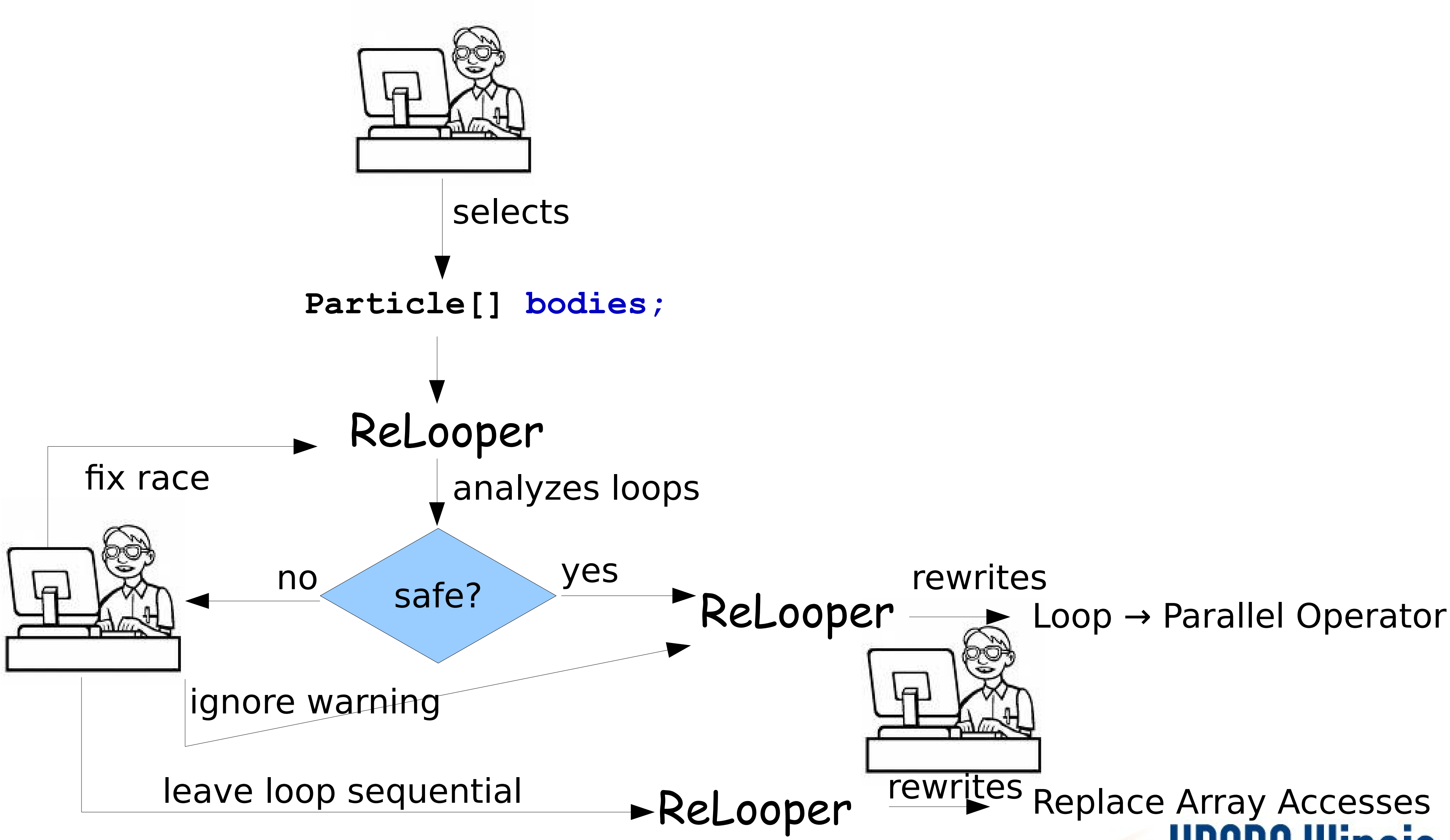
Original Source

```java
public class ParticleComputation {
    Particle[] bodies;

    void compute() {
        bodies = new Particle[10000000];

        for (int i = 0; i < bodies.length; i++) {
            bodies[i] = Particle.createRandom();
        }

        for (int i = 0; i < bodies.length; i++) {
            bodies[i].moveBy(1, 7);
        }

        Particle cm = new Particle(0,0,0);
        for (int i = 0; i < bodies.length; i++) {
            double cmm = cm.m + bodies[i].m;
            double cmx = (cm.x * cm.m + bodies[i].x * bodies[i].m)/cmm;
            double cmy = (cm.y * cm.m + bodies[i].y * bodies[i].m)/cmm;
            cm = new Particle(cmx, cmy, cmm);
        }
    }
}
```

Refactored Source

```java
public class ParticleComputation {
    ParallelArray<Particle> bodies;

    void compute() {
        bodies = ParallelArray.create(10000000, Particle.class, ParallelArr
                .defaultExecutor());

        bodies.replaceWithGeneratedValue(new Ops.Generator<Particle>() {
            public Particle op() {
                Particle elt;
                elt = Particle.createRandom();
                return elt;
            }
        });

        bodies.apply(new Ops.Procedure<Particle>() {
            public void op(Particle elt) {
                elt.moveBy(1, 7);
            }
        });

        Particle cm = new Particle(0,0,0);
        cm = bodies.reduce(new Ops.Reducer<Particle>() {
            public Particle op(Particle cm, Particle elt) {
                double cmm = cm.m + elt.m;
                double cmx = (cm.x * cm.m + elt.x * elt.m)/cmm;
                double cmy = (cm.y * cm.m + elt.y * elt.m)/cmm;
                cm = new Particle(cmx, cmy, cmm);
                return cm;
            }
        }, cm);
    }
}
```

The Refactoring Process using ReLooper



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Immutator: Converting Mutable into Immutable Class

Future Work

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Transformations for Convert to `ParallelArray`

`ParallelArray` provides parallel operations (e.g., `apply`, `reduce`)

- operations are applied in parallel on the elements
- pool of worker threads, dynamically load-balanced

Change type declaration:

```
Particle[] bodies
```

↓

```
ParallelArray<Particle> bodies
```

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Loop Transformations for Convert to ParallelArray

#1. Infer parallel operation

#2. Create element operator

```
for (int i = 0; i < bodies.length; i++) {
    bodies[i].moveBy(1, 7);
}
```

```
bodies.apply(new Ops.Procedure<Particle>()
{
    public void op(Particle elt) {
        elt.moveBy(1, 7);
    }
});
```

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Safety Analysis

`ParallelArray` does not provide any synchronization => potential races

- trust programmer, but verify

1. Check that the loop iterates over all elements of array
   - ParallelArray iterates over all elements, does not guarantee ordering

2. Loop iterations do not have conflicting memory accesses
   - sharing through the Heap

3. Loops do not contain blocking IO
   - writing to a "shared" environment,
   - poor parallel performance

Determine Conflicting Memory Accesses

Shared Object = an object that can be reached from different iterations of a loop (transitive definition)

Goal: determine updates to shared objects = writes to their fields

Modeling the heap: object is a memory location modeled by allocation sites and field dereferences

Data-flow analysis computes set of shared objects at each statement

Interprocedural analysis propagates the sharing information through function calls

Analysis works on bytecodes – handles library calls

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Evaluation

Q1: Does the analysis find problems? Is it fast?

Q2: Does ReLooper save rewriting effort?

Q3: What is the speedup of the refactored code?

Methodology:

- took 7 real-world programs
- used ReLooper to parallelize the computationally intensive loops
- for all the problems reported:
- we checked carefully whether they were genuine and tool did not miss,
- we fixed the races, then re-ran ReLooper to rewrite code

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Results

		Analysis				Transformation			Speedup	
	Size SLOC	Warnings Race(Real)	I C	#Analyzed Methods	Time [sec]	Changed LOC	Par Loops	Seq Loops	1-core	2-core
POS Tagger	35K	8(5)	6	995	35	12	1	1	.97	1.8
Coref	117K	3(0)	7	1147	38	16	1	2	.97	1.9
Monte Carlo	1127	9(9)	0	106	13	15	1	1	.99	1.4
Barnes -Hut	540	2(0)	0	57	4	7	1	0	.98	1.7
Em3d	190	2(0)	6	23	6	16	2	2	.98	1.4
Lucene	51K	10(9)	0	484	17	44	2	6	.99	1.96
JUnit	5.7K	2(0)	0	128	12	10	1	0	.98	1.75

Doug Lea (architect of ParallelArray) writes on the Java concurrency mailing list:

"I was very impressed when Danny demoed ReLooper a few weeks ago at OOPSLA. Some of the sample refactored programs are realistic enough that I expect it will be useful to just about anyone interested in exploring these forms of parallelization"

Download:

http://refactoring.info/tools/ReLooper

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Immutator: Converting Mutable into Immutable Class

Joint work:
F. Kjolstad
G. Acevedo
M. Snir

Future Work

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Immutability Simplifies Parallel Programming

Immutability = transitive state of an object can not be changed after construction

If threads can't change the state of an object, they can share it without any synchronization:

- No races, no locks, no deadlocks (for that class) = no headaches

Immutable classes are embarrassingly thread-safe

Use immutable classes when programming threads, unless you need mutability

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Make Class Immutable

```java
class Circle{
  Point c;
  int r;

  Circle(Point p, int radius){
     this.c = p;
     this.r = radius;
  }

  void moveTo(Point newCenter){
     this.c = newCenter;
  }

  Point getCenter(){
     return c;
  }
}
```

1.
3.
2.
3.

```java
class Circle{
  final Point c;
  final int r;

  Circle(Point p, int radius){
     this.c = p.clone();
     this.r = radius;
  }

  Circle moveTo(Point newCenter){
   return new Circle(newCenter, this.r);
  }

  Point getCenter(){
     return c.clone();
  }
}
```

1. Make all fields final

2. Convert mutator methods into factory methods

3. Clone all entering and escaping objects

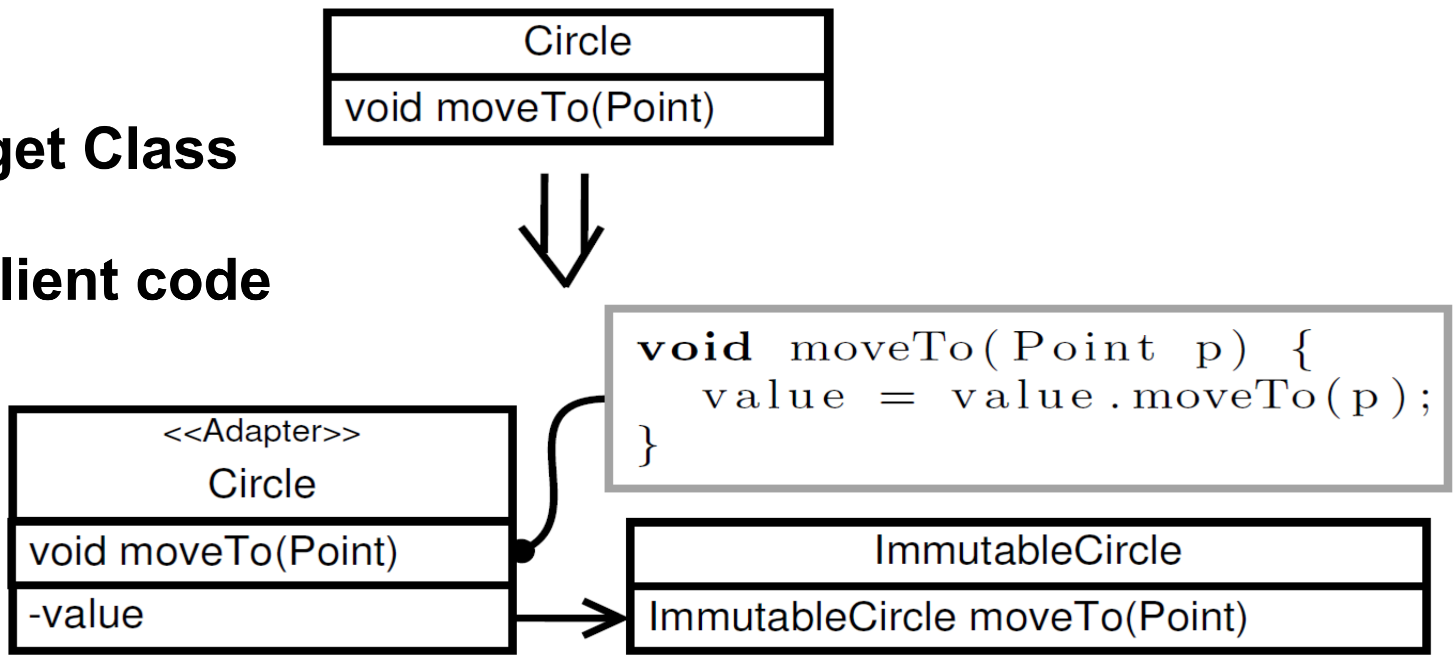
Adapt Client Code to Use Immutable Class

```
Class Client{
....
  circle.moveTo(new Point(1,2));
```

```
Class Client{
....
  circle= circle.moveTo(new Point(1,2));
```

Solution #2:
Adapting the Target Class

- no changes to client code



Immutator's under the Hood Program Analysis

Detecting direct and transitive mutators

- interprocedural method-purity analysis for detecting side-effects on the transitive state of the target class

Detecting entering and escaping objects

- interprocedural class escape analysis for detecting entering/escaping objects that are part of the transitive state of the target class

Analysis works on bytecodes and correctly accounts for library code

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Immutator Evaluation

1. Ran Immutator on 346 classes from open-source projects:

- refactoring is widely applicable (33% of classes meet preconditions)
- refactoring with Immutator is fast (average 2.3 sec/refactoring)
- improves productivity: saves programmer from analyzing 84 methods/refactoring and rewriting 42 lines per refactored class

2. Compared Immutator with 11 manual refactorings performed by developers from 6 open-source projects

- manual refactorings had 24 bugs (forgot to clone subtle entering/escaping objects)
- confirmed with the developers these were real bugs
- developers of `JDigraph` applied our patch

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Other Interactive Transformations for Parallelism

Concurrencer [Dig et al. - ICSE'09] supports three refactorings:

- **convert `int` to `AtomicInteger`**
- **convert `HashMap` to `ConcurrentHashMap`**
- **parallelize sequential divide-and-conquer via `ForkJoinTask` framework**

Evaluation on 6 widely used OSS shows Concurrencer:

- **applies transformations that developers overlooked**
- **refactored code exhibits good speedup**

Currently working to integrate Concurrencer into official Eclipse

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Summary of Current Refactoring Toolset

	Concurrencer	ReLooper	Immutator
Thread-safety	- Convert primitive to Atomic* - Use ConcurrentHashMap		Make class Immutable
Throughput	Recursive fork-join parallelism	Loop parallelism	
Scalability	-Convert primitive to Atomic* -Use ConcurrentHashMap		Make class Immutable

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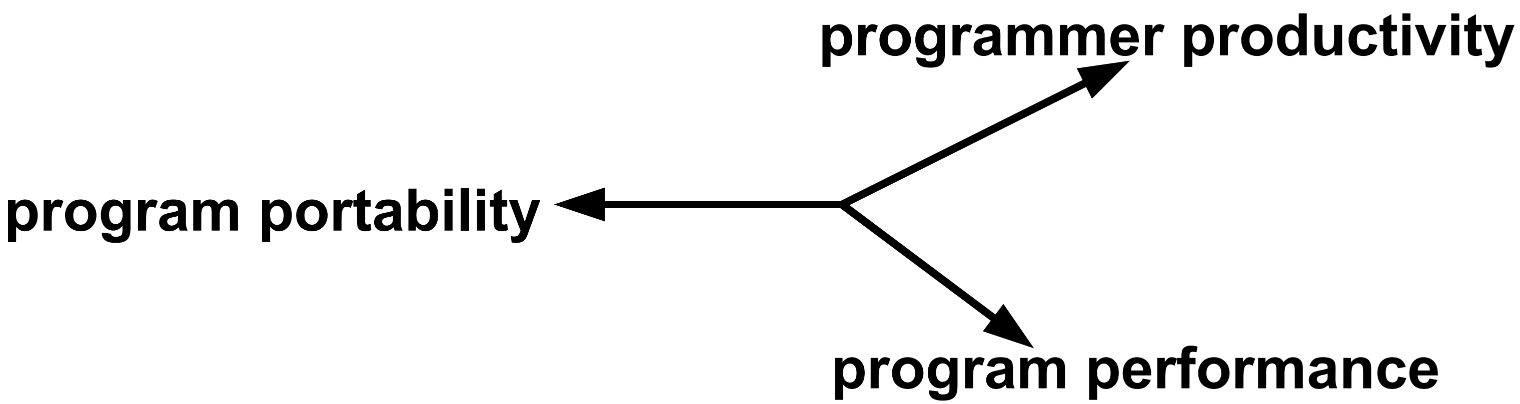
Future Work

Future Work

Refactorings for parallelism

- empower average programmer to safely parallelize programs
- new transformations inspired by problems in industry
- porting tools toward tomorrow's paradigm: shared-memory, distributed memory, cloud

Challenges in research on || programming:



My vision:

treat parallel transformations as first-class citizens

Improving Programmer Productivity by Improving Software Maintenance of Parallel Code

Record transformations in the IDE

Explicit documentation for parallelization

Refactorings leave annotations in code

The IDE can provide two views of the same code

- a simple view for program understanding
- a more complex view for tuning

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Challenges on Providing Multi-Views

Programmer uses:

- sequential view for code understanding, debugging
- performance view for performance debugging, profiling

How to maintain consistency between the two views?

How to seamlessly collect and understand edits?

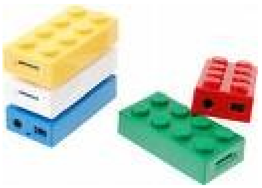
Do edits & transformations in the two views commute?

What kind of annotations are suitable for representing transformations?

How to represent and store programs?

First-class Program Transformations Improves Program Performance

Compose transformations, assemble them in different combinations



Transformations can provide explicit "knobs" for autotuners

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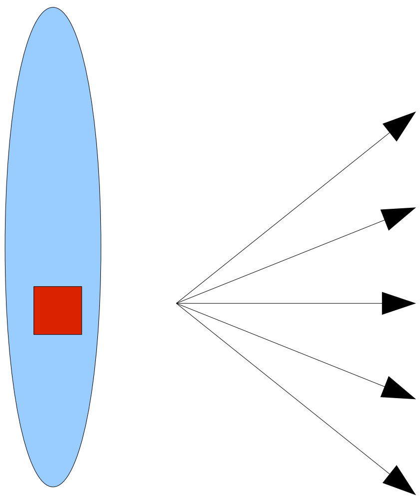
Challenges on Improving Program Performance

How to help programmer parallelize code with conflicting memory updates?



R1: privatize variable

R2: protect with locks

R3: use an Atomic* variable

R4: split loop

R5: custom transformation

loop with a memory dependency

How to search efficiently in the space of optimization vs. safety, and provide best recommendation ?

How to interact seamlessly with other performance tools and the compiler?

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First-class Program Transformations Improves Portability

Easy porting to new platforms

- **same transformation has several platform-specific implementations (e.g., ParallelArray, CloudArray, GPUArray)**

- **keep the portable code separate from the platform-specific transformations**

Challenges:

- **some transformations for a platform can require conflicting restructuring of the code**

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Conclusions

“Change is the only guaranteed constant”

Interactive program transformations can incorporate various change requirements into existing applications (e.g., parallelism)

Convert “introduce parallelism” into “introduce parallel library”

- still tedious, error- and omission-prone

Automated refactoring is more effective than manual refactoring

Today's brand new sequential programs are tomorrow's legacy programs

- evolution becomes the primary paradigm of software development

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