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Lambda Expressions in Java

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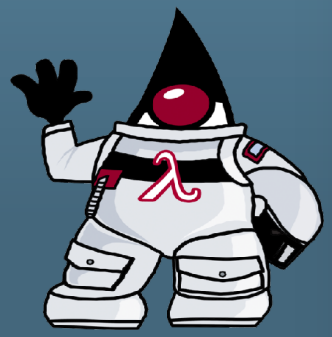
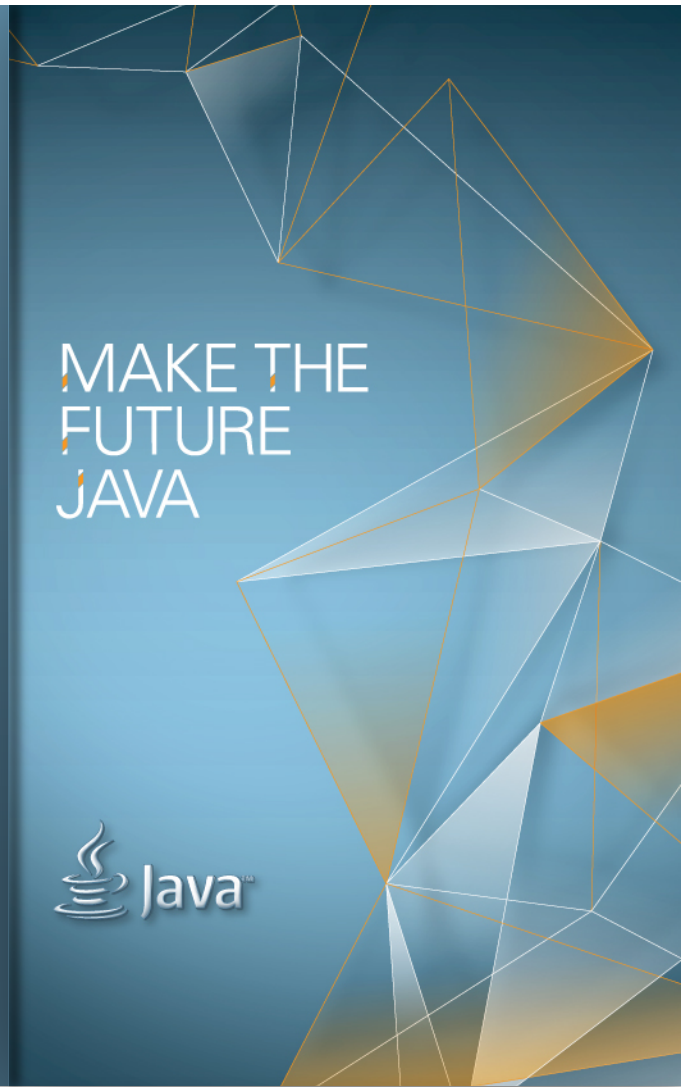


With thanks to Brian Goetz



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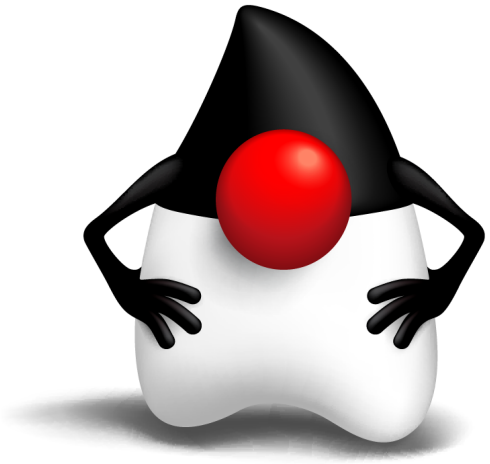
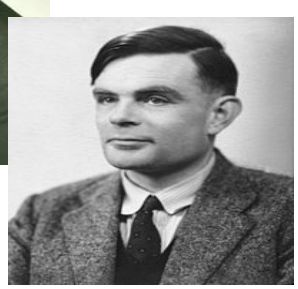
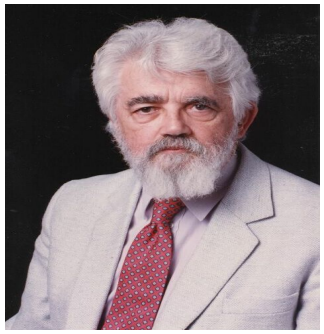
A Bit Of Background







1930/40’s

1950/60’s

1970/80’s

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ARTIFICIAL INTELLIGENCE LABORATORY

AI Memo No. 353 March 10, 1976

LAMBDA

THE ULTIMATE IMPERATIVE

by

Guy Lewis Steele Jr. and Gerald Jay Sussman

Images – wikipedia / bio pages

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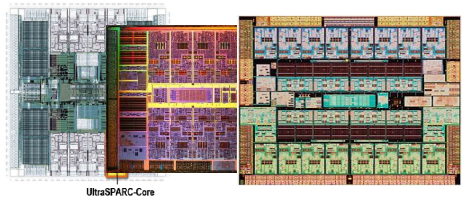
Computing Today

- Multicore is now the default
  - Moore's law means more cores, not faster clockspeed
- We need to make writing parallel code easier
- All components of the Java SE platform are adapting
  - Language, libraries, VM

360 Cores
2.8 TB RAM
960 GB Flash
InfiniBand
..



Dr. Dobb's
THE WORLD OF SOFTWARE DEVELOPMENT

Herb Sutter
http://www.gotw.ca/publications/concurrency-ddj.htm
http://drdobbs.com/high-performance-computing/225402247
http://drdobbs.com/high-performance-computing/219200099

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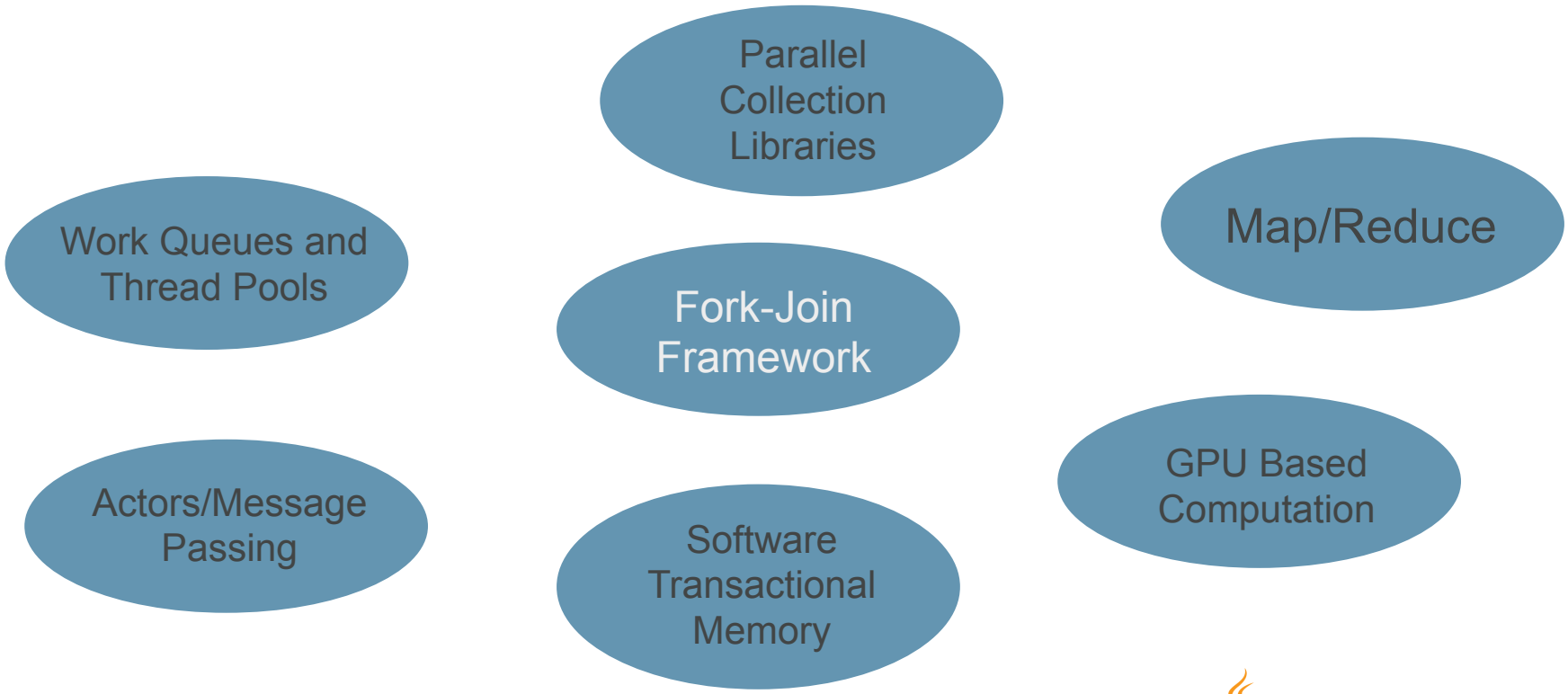
Data Parallelism Solutions



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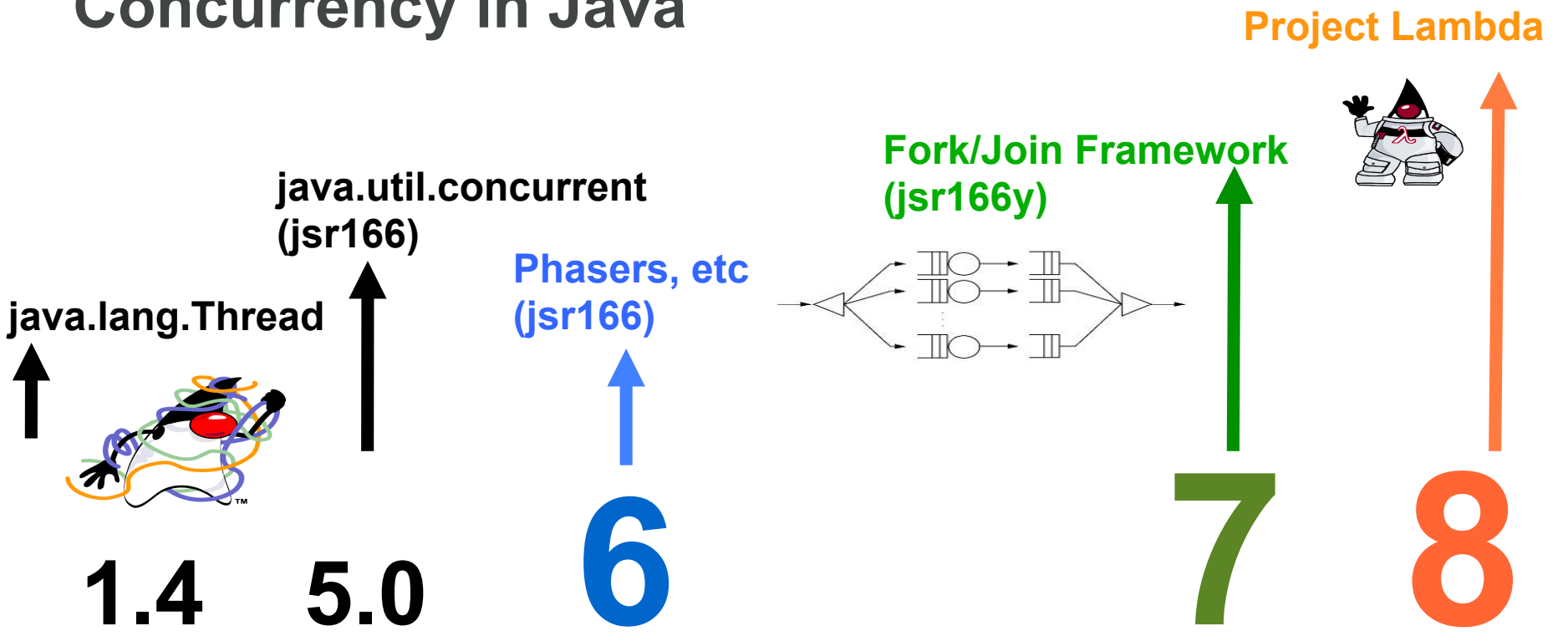
Concurrency in Java



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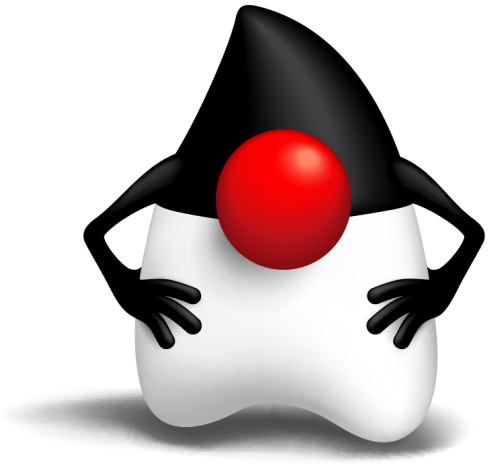
Goals For Better Parallelism In Java

- Easy-to-use parallel libraries
  - Libraries can hide a host of complex concerns
    - task scheduling, thread management, load balancing, etc
- Reduce conceptual and syntactic gap between serial and parallel expressions of the same computation
  - Currently serial code and parallel code for a given computation are very different
    - Fork-join (added in Java SE 7) is a good start, but not enough

It's All About The Libraries

- Most of the time, we should prefer to evolve the programming model through libraries
  - Time to market – can evolve libraries faster than language
  - Decentralized – more library developers than language developers
  - Risk – easier to change libraries, more practical to experiment
  - Impact – language changes require coordinated changes to multiple compilers, IDEs, and other tools
- But sometimes we reach the limits of what is practical to express in libraries, and need some help from the language

Bringing Lambdas To Java



The Problem: External Iteration

```
List<Student> students = ...
double highestScore = 0.0;
for (Student s : students) {
  if (s.gradYear == 2011) {
    if (s.score > highestScore) {
      highestScore = s.score;
    }
  }
}
```

- Client controls iteration
- *Inherently serial:* iterate from beginning to end
- Not thread-safe because business logic is stateful (mutable accumulator variable)

Internal Iteration With Inner Classes

More Functional, Fluent and Monad Like

```
SomeList<Student> students = ...
double highestScore =
  students.filter(new Predicate<Student>() {
    public boolean op(Student s) {
      return s.getGradYear() == 2011;
    }
  }).map(new Mapper<Student,Double>() {
    public Double extract(Student s) {
      return s.getScore();
    }
  }).max();
```

- Iteraction, filtering and accumulation are handled by the library
- Not inherently serial – traversal *may* be done in parallel
- Traversal *may* be done lazily – so one pass, rather than three
- Thread safe – client logic is stateless
- High barrier to use
  - Syntactically ugly

Internal Iteration With Lambdas

```
SomeList<Student> students = ...
double highestScore =
  students.filter(Student s -> s.getGradYear() == 2011)
          .map(Student s -> s.getScore())
          .max();
```

- More readable
- More abstract
- Less error-prone
- No reliance on mutable state
- Easier to make parallel

Lambda Expressions

Some Details

- Lambda expressions are anonymous functions
  - Like a method, has a typed argument list, a return type, a set of thrown exceptions, and a body

```
double highestScore =
  students.filter(Student s -> s.getGradYear() == 2011)
          .map(Student s -> s.getScore())
          .max();
```

Lambda Expression Types

- Single-method interfaces used extensively to represent functions and callbacks
  - Definition: a *functional interface* is an interface with one method (SAM)
  - Functional interfaces are identified structurally
  - The type of a lambda expression will be a functional interface

```
interface Comparator<T>  { boolean compare(T x, T y); }
interface FileFilter     { boolean accept(File x); }
interface DirectoryStream.Filter<T> { boolean accept(T x); }
interface Runnable       { void run(); }
interface ActionListener { void actionPerformed(…); }
interface Callable<T>    { T call(); }
```

Target Typing

- A lambda expression is a way to create an instance of a functional interface
  - Which functional interface is inferred from the context
  - Works both in assignment and method invocation contexts
    - Can use casts if needed to resolve ambiguity

```
Comparator<String> c = new Comparator<String>() {
    public int compare(String x, String y) {
        return x.length() - y.length();
    }
};
```

```
Comparator<String> c = (String x, String y) -> x.length() - y.length();
```

Local Variable Capture

- Lambda expressions can refer to *effectively final* local variables from the enclosing scope
  - Effectively final means that the variable meets the requirements for final variables (e.g., assigned once), even if not explicitly declared final
  - This is a form of type inference

```
void expire(File root, long before) {
    ...
    root.listFiles(File p -> p.lastModified() <= before);
    ...
}
```

Lexical Scoping

- The meaning of names are the same inside the lambda as outside
  - A ‘this’ reference – refers to the enclosing object, not the lambda itself
  - Think of ‘this’ as a final predefined local

```
class SessionManager {
  long before = ...;

  void expire(File root) {
     ...
     // refers to ‘this.before’, just like outside the lambda
     root.listFiles(File p -> checkExpiry(p.lastModified(), before));
  }

  boolean checkExpiry(long time, long expiry) { ... }
}
```

Type Inferrence

- Compiler can often infer parameter types in lambda expression

```
Collections.sort(ls, (String x, String y) -> x.length() - y.length());
```

```
Collections.sort(ls, (x, y) -> x.length() - y.length());
```

- Inferrence based on the target functional interface's method signature
- Fully statically typed (no dynamic typing sneaking in)
  - More typing with less typing

Method References

- Method references let us reuse a method as a lambda expression

```
FileFilter x = new FileFilter() {
  public boolean accept(File f) {
    return f.canRead();
  }
};
```

```
FileFilter x = (File f) -> f.canRead();
```

```
FileFilter x = File::canRead;
```


Putting it all together

With a little help from the libraries

- Make common idioms more expressive, reliable, and compact

```
Collections.sort(people, new Comparator<Person>() {
    public int compare(Person x, Person y) {
        return x.getLastName().compareTo(y.getLastName());
    }
});
```

More concise
More abstract
More reuse
More object-oriented

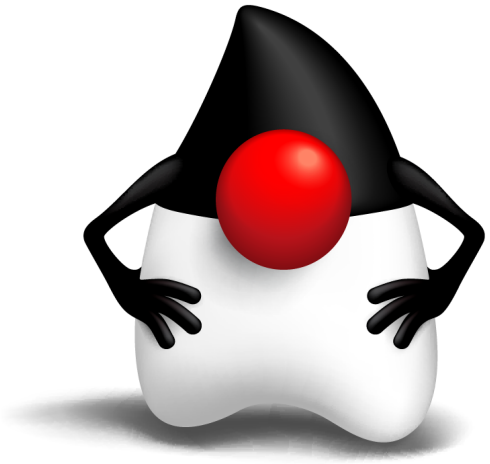
```
Collections.sort(people,
                 comparing(p -> p.getLastName()));
```


Lambda Expressions In Java

Advantages

- Developers primary tool for computing over aggregates is the for loop
  - Inherently serial
  - We need internal iteration
- Useful for many libraries, serial and parallel
- Adding Lambda expressions to Java is no longer a radical idea

Library Evolution



Library Evolution

The Real Challenge

- Adding lambda expressions is a big language change
  - If Java had them from day one, the APIs would definitely look different
  - Adding lambda expressions makes our aging APIs show their age even more
- Most important APIs (Collections) are based on interfaces
  - How to extend an interface without breaking backwards compatability
- Adding lamabda expressions to Java, but not upgrading the APIs to use them, would be silly
- Therefore we also need better mechanisms for *library evolution*

Library Evolution Goal

- Requirement: aggregate operations on collections
  - New methods on Collections that allow for bulk operations
  - Examples: filter, map, reduce, forEach, sort
  - These can run in parallel (return Stream object)

```
int heaviestBlueBlock =
    blocks.filter(b -> b.getColor() == BLUE)
          .map(Block::getWeight)
          .reduce(0, Integer::max);
```

- This is problematic
  - Can't add new methods to interfaces without modifying all implementations
  - Can't necessarily find or control all implementations

API Evolution Is A First-Class Problem

- Interfaces are a double-edged sword
  - Once published, cannot add to them without breaking existing implementations
- Fundamental problem: can't evolve interface-based APIs
  - The older an API gets, the more obvious the decay
  - We're a victim of our own success; Java has lots of old APIs
  - Lots of bad choices here
    - Let the API stagnate
    - Try and replace it in entirety – every few years!
    - Nail bags on the side (e.g., Collections.sort())
- Key Principle: burden of API evolution should fall to implementors, not users
  - Solutions that require users to permanently cruft up their code to use new features are undesirable

Solution: Virtual Extension Methods

AKA Defender Methods

- Specified in the interface
- From the caller's perspective, just an ordinary interface method
- List class provides a default implementation
  - Default is only used when implementation classes do not provide a body for the extension method
  - Implementation classes can provide a better version, or not
- Drawback: requires VM support

```
interface List<T> {
    void sort(Comparator<? super T> cmp)
        default { Collections.sort(this, cmp); };
}
```

Virtual Extension Methods

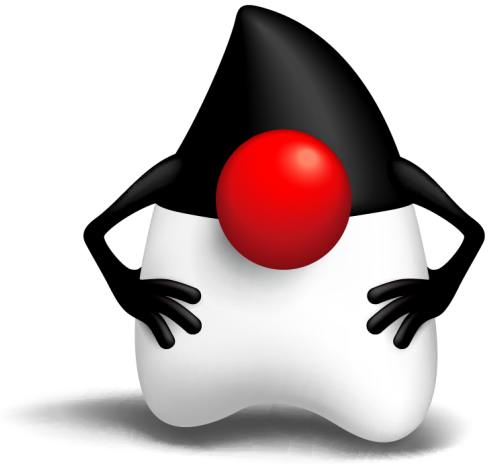
Stop right there!

- Err, isn't this implementing multiple inheritance for Java?
  - Yes, but Java already has multiple inheritance of *types*
  - This adds multiple inheritance of *behavior* too
  - But not *state*, which is where most of the trouble is
  - Though can still be a source of complexity due to separate compilation and dynamic linking

Compatibility Goals

- Extension methods are about being able to *compatibly* evolve APIs
  - Motivated by having APIs in serious need of evolution
- Compatibility has multiple faces
  - Source compatibility
  - Binary compatibility
- Primary concern is *adding new methods with defaults* to existing interfaces
  - *Without* necessarily recompiling the implementation class
- Secondary concerns
  - Adding defaults to existing methods
  - Changing defaults on existing extension methods
    - Removals of most kinds are unlikely to be compatible

Lambda Implementation
(Looking under the hood)



Lambda Implementation Approaches

- A lambda statement by definition can always be replaced by a single abstract method type
- Therefore there are several possible approaches to implementation
  - Desugar to an anonymous inner class
  - Use method handles
  - Use dynamic proxies
  - Use invokedynamic
  - Others

Anonymous Inner Class

Direct Compiler Translation

```
s -> s.getGradYear() == 2011

class StudentReduce$1 implements Predicate<Student> {
  public boolean apply(Student s) {
    return (s.getGradYear() == 2011);
  }
}
```

- Capture == invoke constructor
- One class per lambda expression (not nice)
- Burdens lambdas with identity
- No improvement in performance over current idiom

Translate Directly To Method Handles

- Compiler converts lambda body to a static method
  - Variable capture adds parameters to method signature
  - Capture == take method reference and curry the captured arguments
  - Invocation == MethodHandle.invoke

Translation Options

Issues

- Whatever translation is used is not just an implementation, but becomes a binary specification
  - Backwards binary compatability is important
  - Is the MethodHandle API ready to become a permanent binary specification
  - Performance of raw method handles compared to anonymous inner classes

More Translation Options

- Start with inner classes, switch to method handles later
  - Older compiled classes would still have inner classes
  - Java has never had “recomile your code for better performance”
  - We don’t want to start now
- We need a fixed solution
  - Old technology is bad
  - New technology is not mature enough
  - What to do?

Invokedynamic

Not just for dynamically typed languages

- Delay the translation strategy to runtime
- Invokedynamic embeds a recipe for constructing a lambda at the capture site
  - A declerative recipe, not an imperative recipe
  - Static bootstrap code: lambda meta-factory
  - At first capture a strategy is chosen and the call site linked
  - Subsequent captures use the method handle and bypass the slow path
  - Added bonus: stateless lambdas translate to static loads
    - Meta-factory returns reference to single instance

Lambda Performance Costs

- Linkage cost
- Capture cost
- Invocation cost

- The key cost to optimise is the *invocation* cost

Code Generation Strategy

- All lambda definitions are converted to static methods
  - For non-capturing lambdas the lambda signature matches the SAM signature exactly

```
s -> s.getGradYear() == 2011
```

  - Translated to Predicate<Student> becomes:

```
static boolean lambda$1(Student s) {
  return s.getGradYear() == 2011;
}
```

Code Generation Strategy

- For lambdas that capture variables from the enclosing context, these are prepended to the argument list
  - Only effectively final variables can be captured
  - Freely copy variables at point of capture

```
s -> s.getGradYear() == tagetYear
```

  - When translated to Predicate<String>:

```
static boolean lambda$1(int targetYear, Student s) {
  return s.getGradYear() == targetYear;
}
```

Code Generation Strategy

- At point of lambda capture compiler emits an invokedynamic call to create SAM (lambda factory)
  - Call arguments are captured variables (if any)
  - Bootstrap is method in language runtime (meta-factory)
  - Static arguments identify properties of the lambda and SAM

```
list.filter(s -> s.getGradYear() == tagetYear)
```

  - Becomes

```
list.filter(indy[bootstrapmethod=metafactory, args=…](targetYear));
```

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Runtime Translation Strategies

- Generate inner class dynamically
  - Same class that would be created by the compiler, bu generated at runtime
  - Probable initial strategy before optimisation
- generate per-SAM wrapper class
  - One per SAM type, not one per lambda expression
  - Use method handles for invocation
  - Use ClassValue to cache wrapper for SAM
- Use dynamic proxies
- Use MethodHandleProxies.asInterfaceInstance
- Use a VM private API to build object from scratch

Conclusions

- Java needs lambda statements for multiple reasons
  - Significant improvements in existing libraries are required
  - Replacing all the libraries is a non-starter
  - Compatibly evolving interface-based APIs has historically been a problem
- Require a mechanism for interface evolution
  - Solution: virtual extension methods
  - Which is both a language and a VM feature
  - And which is pretty useful for other things too
- Java SE 8 evolves the language, libraries, and VM together


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