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# Lambda Expressions in Java ME Embedded

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# Program Agenda

1. Java ME Embedded Overview
2. Dreaming of Lambdas in ME
3. Dreams come true
4. Alternatives

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# Java ME Embedded

**Key Principles**

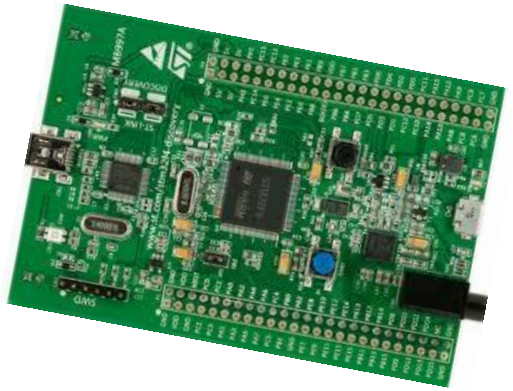
- Java ME 8 is the “little sibling” of Java SE 8
- Portability of applications and libraries across the Java Platform
- Java ME vs. Java SE is a footprint/functionality tradeoff
- Java ME & Java SE release cycles are in sync

**Benefits**

- Modern and flexible platform for delivering embedded software
- Unified development experience & community across Java
- Aligned Java language, core APIs, development, and tools
- Enable 9+ Million Java developers to develop for Java Embedded

# Java ME Embedded Target Devices

- Wide range of embedded hardware from MCU to gateways and wireless modules
- Target CPUs are ARM 9, 11, Cortex-A/M3/M4
- Constrained memory (128K – 32M RAM, from 1M of ROM/Flash)
- Variety of peripherals
- Minimal OS requirement
  - Single process
  - Single native thread
  - “Bare metal” is possible



# Java ME 8 Platform Overview

**Additonal APIs (Examples)**

- Messaging
- Wireless Communication
- Protocols and Data Conversion
- Security and Management
- Additional Optional APIs
- Location
- Web Services
- Sensors
- Additional Optional JSRs
- Vertical Specific APIs

**On-Device I/O Access**

- Device I/O API

**Application Platform**

- **Java ME Embedded Profile** (MEEP 8, JSR 361)

**Security and Trust Services**

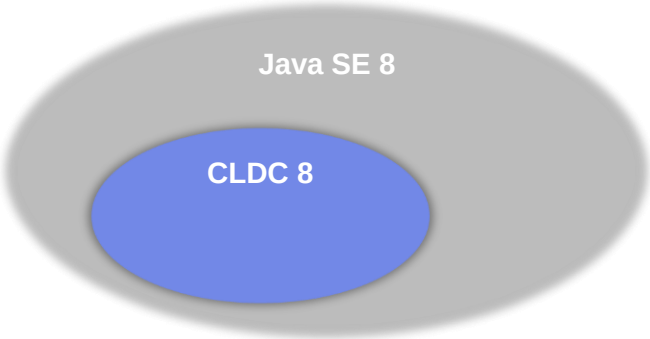
- SATSA

**Java VM**

- **Java ME CLDC 8** (JSR 360, aligned with Java SE 8)

# CLDC 8 High-Level Overview

- Description
  - CLDC 8 is revolutionary update for CLDC 1.1.1 that brings the VM, Java language and core API libraries in alignment with Java SE 8
- Key Features
  - Synchronize Java SE 5/6/7/8 language features into ME
  - Introduce community requested Java SE API library features
  - Virtual Machine update, support latest class file format
  - More footprint optimizations and options
- Specification Requirements
  - CLDC 8 to be an extended strict subset of Java SE 8
  - Consolidated Generic Connection Framework (GCF)
  - Backward binary compatible



# CLDC HI VM Implementation

- Implements CLDC 8 Specification (JSR360)
- Optimized assembly interpreter
- Optimizing dynamic adaptive and ahead-of-time compilers
- Generational mark’n’compact GC
- Single native thread, multiple Java threads, fair scheduler
- Multitasking (MVM) with isolation and memory quotas
- Minimized Footprint
  - compact data structures
  - aggressive build-time optimizations for footprint and performance

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# What is Lambda Expression?

- Lambda expression introduced as language feature in Java 8
- Functional interface is an interface with exactly one abstract method
- Lambda expression is a block of code with parameters that can be executed and referenced
- Lambda expression is treated by VM runtime as an instance of a functional interface
- Lambda expression can capture effectively final variables from the enclosing scope

# Sample: Inner Class vs. Lambda Syntax

```
String data[] = {“orange", “apple", “carrot"};
```

```
Arrays.sort(data, new Comparator<String>() {
    public int compare(String s1, String s2) {
        return s1.compareTo(s2);
    }
});
```

```
Arrays.sort(data, (s1, s2) -> s1.compareTo(s2));
```

```
Arrays.sort(data, String::compareTo);
```

# Why Lambdas are Wanted in Java ME

- Common reasoning for Java
  - General purpose languages support functional programming paradigm
  - Anonymous classes can help, but syntax is cumbersome
  - Less text - less errors, neat syntax of Java lambdas
  - More optimal data processing by VM is possible
- Java ME Embedded reasons
  - Inner classes are heavy, lambdas can be more efficient
  - Easier to port any Java code from SE to ME
  - Development experience consistent with Java SE

# Lambda expression friends

- Default interface methods (Defender methods)
  - Allow interface to evolve without breaking the existing code

```
public interface Iterable<T> {
  public default void forEach(Consumer<? super T> consumer) {
    for (T t : this) {
      consumer.accept(t);
}}}
```

- Method reference
  - Allows to use an existing method as lambda expression
  - Static, instance methods and constructors can be referred

```
Comparator<String> comparator = String::compareTo;
```

- Collections updated for lambdas, bulk operations and parallelization

# What is Missing in CLDC 8 Spec for Lambdas?

- CLDC 8 is more close to SE 7 rather than to SE 8
- No invokedynamic support by CLDC VM
- Lambdas are not supported by the CLDC 8 spec
  - Inner classes were generated for lambdas by early javac versions
  - Retrolambda tool to backport Java 8 ‘s lambdas to Java 7, 6 and 5
    https://github.com/orfjackal/retrolambda
- No default interface methods support
- Collections are minimalistic

# Not the Goals for Java ME Embedded

- Parallel data processing makes sense if multiple CPU cores are engaged
- Limited invokedynamic support is enough for Java lambdas
  - Only small subset of java.lang.invoke API is referenced by the Java compiler to implement lambdas in generated class files

    CallSite, MethodHandle, MethodHandles, MethodType, LambdaMetaFactory, LambdaConversionException
  - Non-Java dynamic languages support is not the goal for Java ME Embedded VM
- No goal to provide java.lang.invoke API for developers, for javac only
- Lambdas serialization is out of scope

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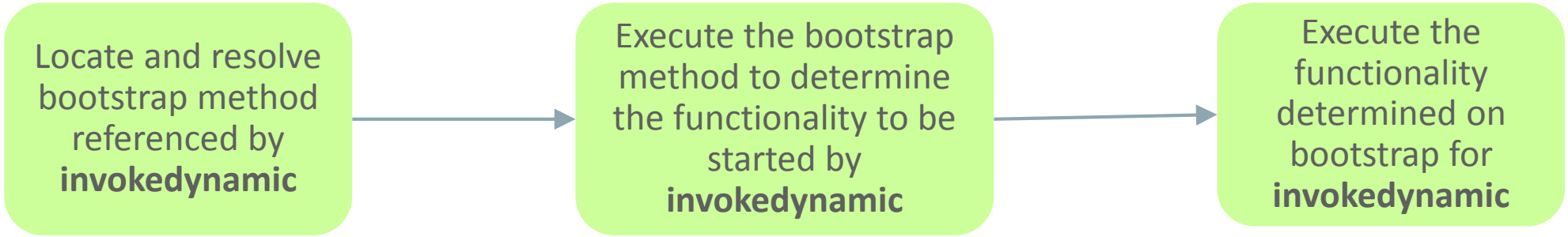
# CLDC HI VM Evolution towards Lambdas

- Lambdas are compiled by javac 8 into bytecodes using invokedynamic
- Java compiler does a lot, but not all – VM & runtime support is needed
- Class file parsing is updated to support
  - new constant pool tags and structures (see JVMS 8)
    CONSTANT_MethodHandle, CONSTANT_MethodType, CONSTANT_InvokeDynamic, …
  - invokedynamic bytecode instruction
- Execution of invokedynamic is added to the VM
- Runtime libraries update for lambdas
  - collections, java.util.function API, …

# Intro for invokedynamic

- Introduced in JVMS 7 and designed to determine at runtime what functionality to be executed on method invocation
- References bootstrap method to be called on the first execution
- The bootstrap method resolves what should be executed this and the next times the instruction is executed by the VM



# Lambdas Support in Java ME Embedded

- Java compilation of lambda expressions (by javac)
- Runtime execution of lambda expressions by CLDC HI VM

# Java Compilation of Lambdas (by javac)

- Each lambda expression is matched with proper functional interface
- The body of lambda expression is “desugared” into private static method of container class
- Context captured by the lambda expression is presented as extra parameters of the “desugared” method
- Invocation of the lambda expression is generated using invokedynamic bytecode

# Runtime Execution of Lambdas by CLDC HI VM

- The bootstrap method of invokedynamic generates synthetic Java class at runtime on the first invocation of the lambda expression
  - The synthetic class implements the functional interface of the lambda
  - The context captured by the lambda is presented as private members of the class
  - The class constructor accepts the captured context values
  - The main functional method of the class is implemented as the call of the “desugared” lambda body
  - On the call the parameters adaptation is done, the captured context is passed
- The bootstrap method resolves invokedynamic into the call of constructor of the synthetic class generated for the lambda, captured context passed

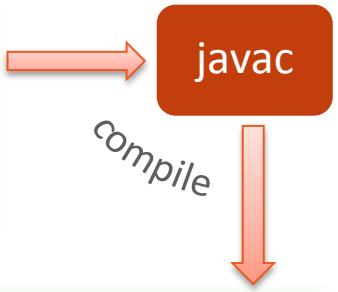
# Runtime Execution of Lambdas by CLDC HI VM (cont.)

- The result of the invokedynamic execution is new instance of the synthetic class pushed onto the Java execution stack
- The synthetic class is reused on each next invocation of the lambda, new instance is created each time
- Unused synthetic classes of lambdas can be collected by GC
- The bootstrap to be started again for lambdas have been executed already, but whose synthetic classes have been collected already

# Sample: Lambda and invokedynamic

Sample.java

```
public class Sample {
  static void main(String[] args) {
    new Thread(
      () -> System.out.println("Hello World!")
    ).start();
  }
}
```

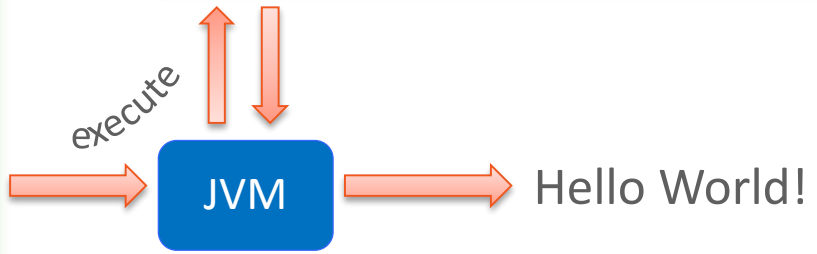



Sample.class

```
public class Sample
  flags: ACC_PUBLIC, ACC_SUPER {

  public static void main(java.lang.String[]);
    descriptor: ([Ljava/lang/String;)V
    Code:
      stack=3, locals=1, args_size=1
         0: new java/lang/Thread
         3: dup
         4: invokedynamic InvokeDynamic #0:run:()Ljava/lang/Runnable;
         9: invokespecial java/lang/Thread."<init>":(Ljava/lang/Runnable;)V
        12: invokevirtual java/lang/Thread.start:()V
        15: return

  private static void lambda$main$0();
    descriptor: ()V
    Code:
      stack=1, locals=0, args_size=0
         0: getstatic java/lang/System.out:Ljava/io/PrintStream;
         3: ldc "Hello World!"
         5: invokevirtual java/io/PrintStream.println:()V
         8: return
}
```

Synthetic

```
final class Sample$$Lambda$1 implements java.lang.Runnable
  flags: ACC_FINAL, ACC_SUPER, ACC_SYNTHETIC {

  private Sample$$Lambda$1();
    descriptor: ()V
    flags: ACC_PRIVATE
    Code:
      stack=1, locals=1, args_size=1
         0: aload_0
         1: invokespecial java/lang/Object."<init>":()V
         4: return

  public void run();
    descriptor: ()V
    flags: ACC_PUBLIC
    Code:
      stack=0, locals=1, args_size=1
         0: invokestatic Sample.lambda$main$0:()V
         3: return
}
```



# Even More Support for Lambdas by CLDC HI VM

- Default and static interface methods are supported by CLDC HI VM
- Method references can be used as lambda expressions
- java.lang.invoke API is not provided for developers, for VM only
- Marker interfaces are supported, serialization not

```
interface Marker {}
@FunctionalInterface interface Action { void run(); }
Action a = (Action & Marker)(() -> System.out.println()));
```

- Lambda expressions dynamic compilation at runtime and ahead-of-time
- Optional lambdas preloading for system code (romization)

# What CLDC HI VM can do differently from SE 8

- The synthetic class for lambda is more lightweight then a standard class
  - Loaded and pre-initialized on synthesis
  - Synthetic method calls to be quickened
- Bare minimum of java.lang.invoke.LambdaMetaFactory functionality is supported by CLDC HI VM
- java.lang.invoke API types CallSite, MethodType, MethodHandle, etc. are used as internal marker types, not instantiated indeed
  - Instead of CallSite creation on bootstrap constant pool entry of the invokedynamic is updated with synthetic class ID

# Proposed CLDC 8+ Spec Changes for Lambdas

- Define strict subset of java.lang.invoke API sufficient for Java lambdas
- Define limited invokedynamic support by VM
- Remove limitations on class file data structures used by invokedynamic
- Remove BootstrapMethods attribute from the unsupported attributes list
- Introduce API changes implied by lambda: collections, java.util.function API subset, …
- Support default and static methods of interfaces

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# Classless Alternative for Lambda Implementation

- No class generation at runtime on invokedynamic bootstrap
- The predefined VM internal polymorphic class that can mimic any functional interface is used instead, not Java class indeed
- Instances of the polymorphic class are created for lambda invocations
- Adapter methods for lambda body calls have to be generated still
- Efficiency for expected popular use cases of lambda expressions
- With bridge methods and marker interfaces it gets closer to regular classes
- Not entirely spec compliant

# Conclusions

- CLDC 8 Spec to be updated for lambda expressions support
- CLDC HI VM team researched different ways to implement lambdas expressions efficiently
- CLDC HI VM development builds implement lambdas in the way aligned with standard Java tools and concepts
- The future Java ME Embedded platforms will provide lambda expressions support

# References

- Oracle Java ME Embedded Platform (OTN)
  http://www.oracle.com/technetwork/java/embedded/javame/embed-me/overview/index.html
- Java ME Embedded 8
  http://docs.oracle.com/javame/8.0/index.html
- CLDC 8 Specification (JSR 360)
  https://jcp.org/en/jsr/detail?id=360
- Java ME blogs:
  - Alexander Belokrylov - https://blogs.oracle.com/javame/
  - Terrence Barr - http://terrencebarr.wordpress.com/

# Q & A

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