Static and Dynamic Program Analysis Using WALA (T.J. Watson Libraries for Analysis)

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PLDI 2010 Tutorial

`http://wala.sf.net`

WALA
T. J. WATSON LIBRARIES FOR ANALYSIS

What is WALA?

- **Java libraries for static and dynamic program analysis**
- **Initially developed at IBM T.J. Watson Research Center**
- **Open source release in 2006 under Eclipse Public License**
- **<u>Key design goals</u>**
  - **Robustness**
  - **Efficiency**
  - **Extensibility**

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(Some) Previous Uses of WALA

- **Research**
  - **over 40 publications from 2003-present**
  - **Including one at PLDI’10 (MemSAT)**
  - `http://wala.sf.net/wiki/index.php/Publications.php`
- **Products**
  - **Rational Software Analyzer: NPEs (Loginov et al. ISSTA’08), resource leak detection (Torlak and Chandra, ICSE’10)**
  - **Rational AppScan: taint analysis (Tripp et al., PLDI’09), string analysis (Geay et al., ICSE’09)**
  - **Tivoli Storage Manager: Javascript analysis**
  - **WebSphere: analysis of J2EE apps**

WALA Features: Static Analysis

- Pointer analysis / call graph construction
  - Several algorithms provided (RTA, variants of Andersen's analysis)
  - Highly customizable (e.g., context sensitivity policy)
  - Tuned for performance (time and space)
- Interprocedural dataflow analysis framework
  - Tabulation solver (Reps-Horwitz-Sagiv POPL'95) with extensions
  - Also tuned for performance
- Context-sensitive slicing framework
  - With customizable dependency tracking

Other Key WALA Features

- **Multiple language front-ends**
  - **Bytecode**: Java, .NET (internal)
  - **Source (CAst)**: Java, Javascript, X10, PHP (partial, internal), ABAP (internal)
  - Add your own!
- **Generic analysis utilities / data structures**
  - Graphs, sets, maps, constraint solvers, …
- **Limited code transformation**
  - Java bytecode instrumentation via Shrike
  - But, main WALA IR is immutable, and no code gen provided
    - designed primarily for computing analysis info

What We'll Cover

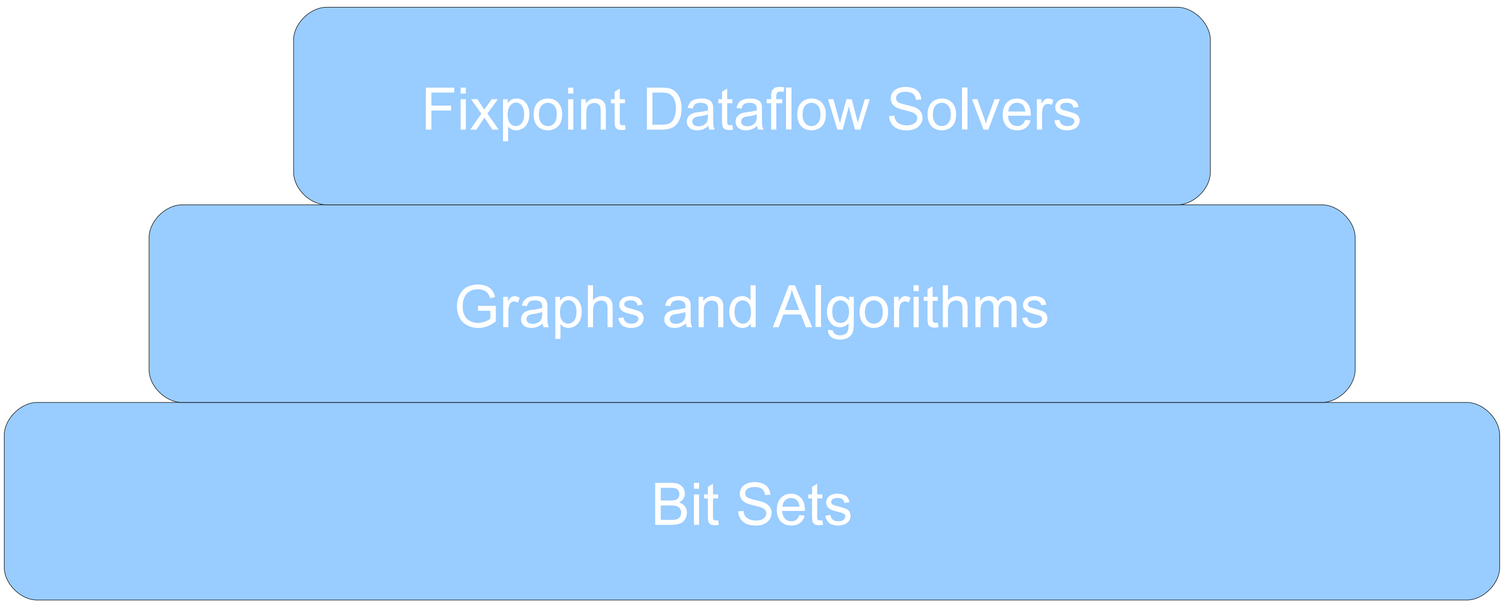
- Overviews of main modules
  - Important features
  - Key class names
  - How things fit together
  - How to customize
- "Deep dives" into real code
  - Interprocedural dataflow analysis example
  - CAst Javascript front-end

How to get WALA

- Walkthrough on "Getting Started" page at `wala.sf.net`
- Code available in SVN repository
  - Trunk or previous tagged releases
  - Split into several Eclipse projects, e.g., `com.ibm.wala.core`, `com.ibm.wala.core.tests`
- Dependence on Eclipse
  - Easiest to build / run from Eclipse, but command line also supported
  - Runtime dependence on some Eclipse plugins (progress monitors, GUI functionality, etc.); must be in classpath

GENERAL UTILITIES

WALA Data Structures



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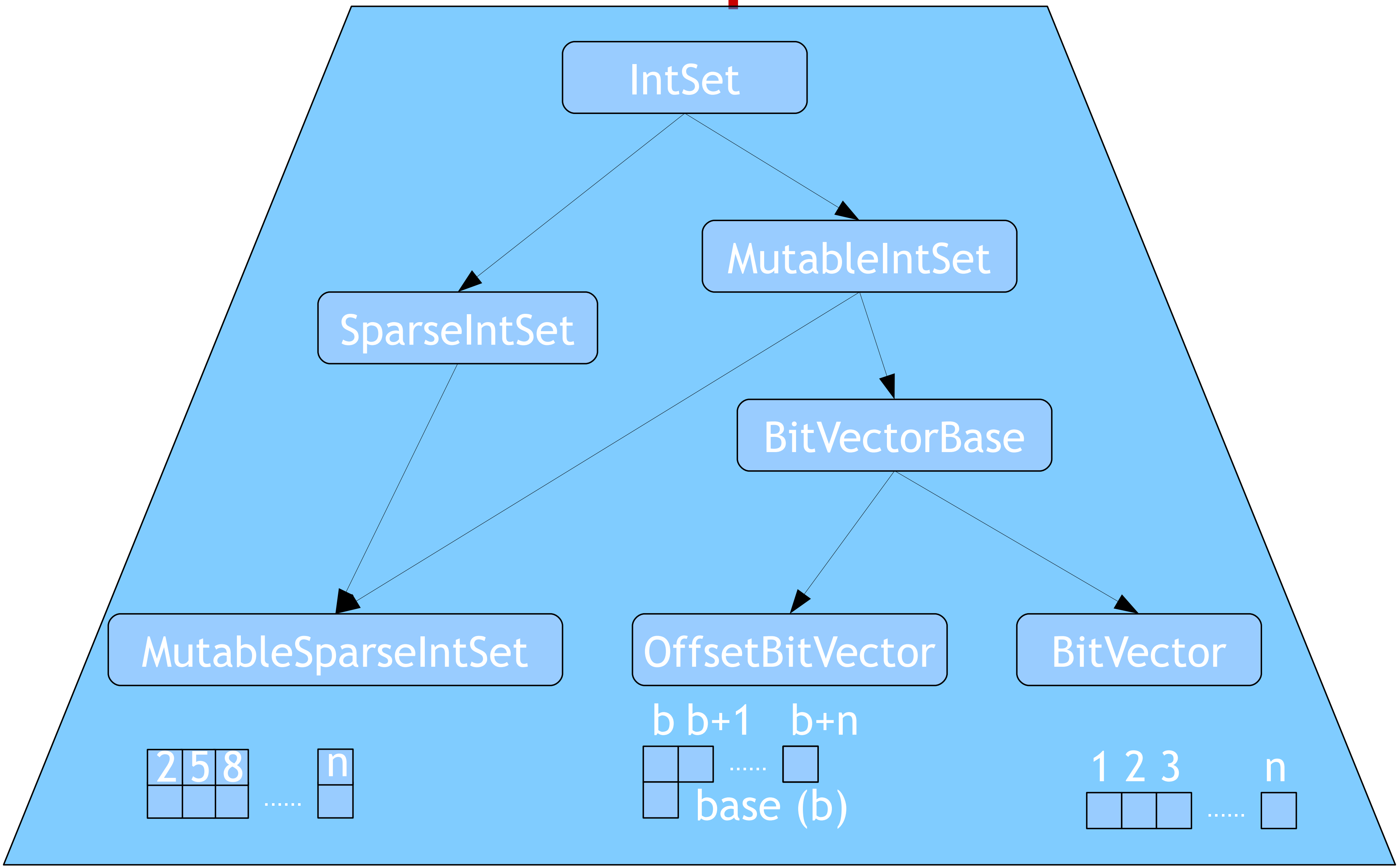
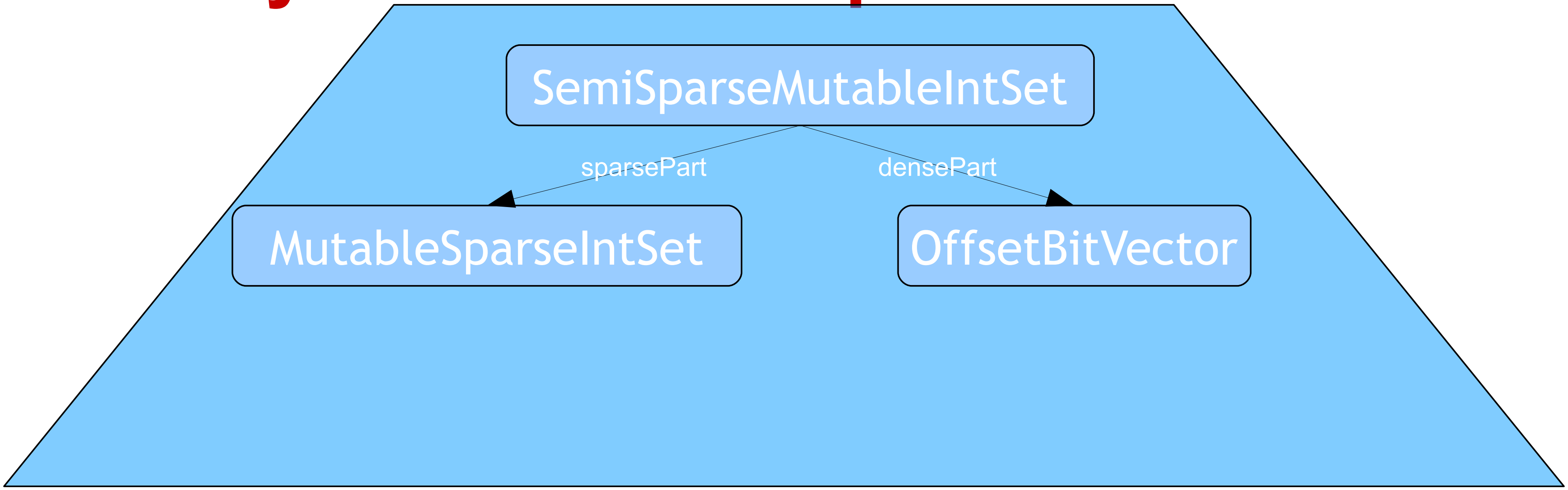
Basic Bit Set Representations



Hybrid Bit Set Representation



Split bitset to save space using dense and sparse parts

- **Dense words: (max – min) / bits per word**
- **Sparse words: number of set bits**
- **Calculate best use of a single dense portion**
- **Rebalance on mutation, amortizing to save cost**

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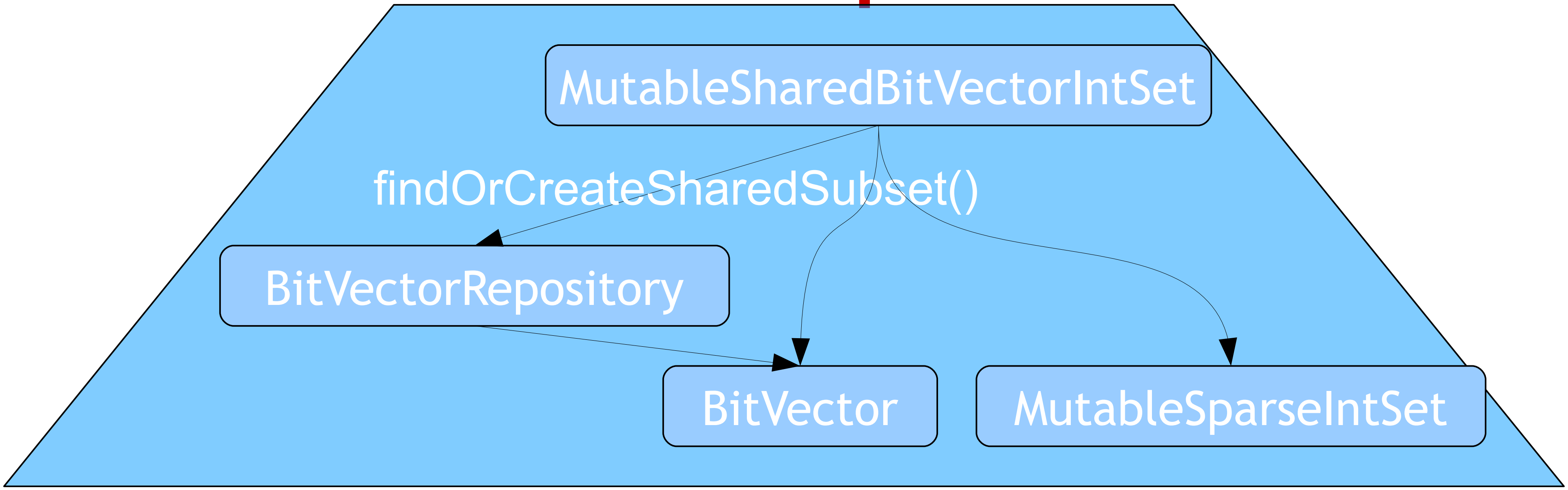
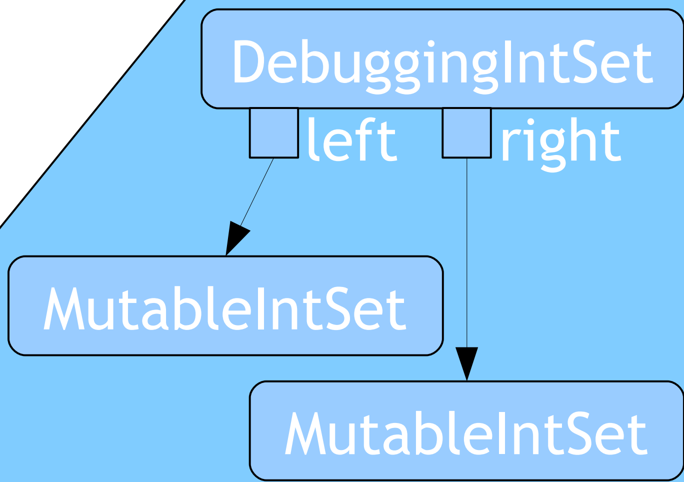
Shared Bit Set Representation



Save space by sharing common portions of bit sets
- **State split into common and private portions**
- **Repository manages set of common portions**
- **Common portions come and go on demand**

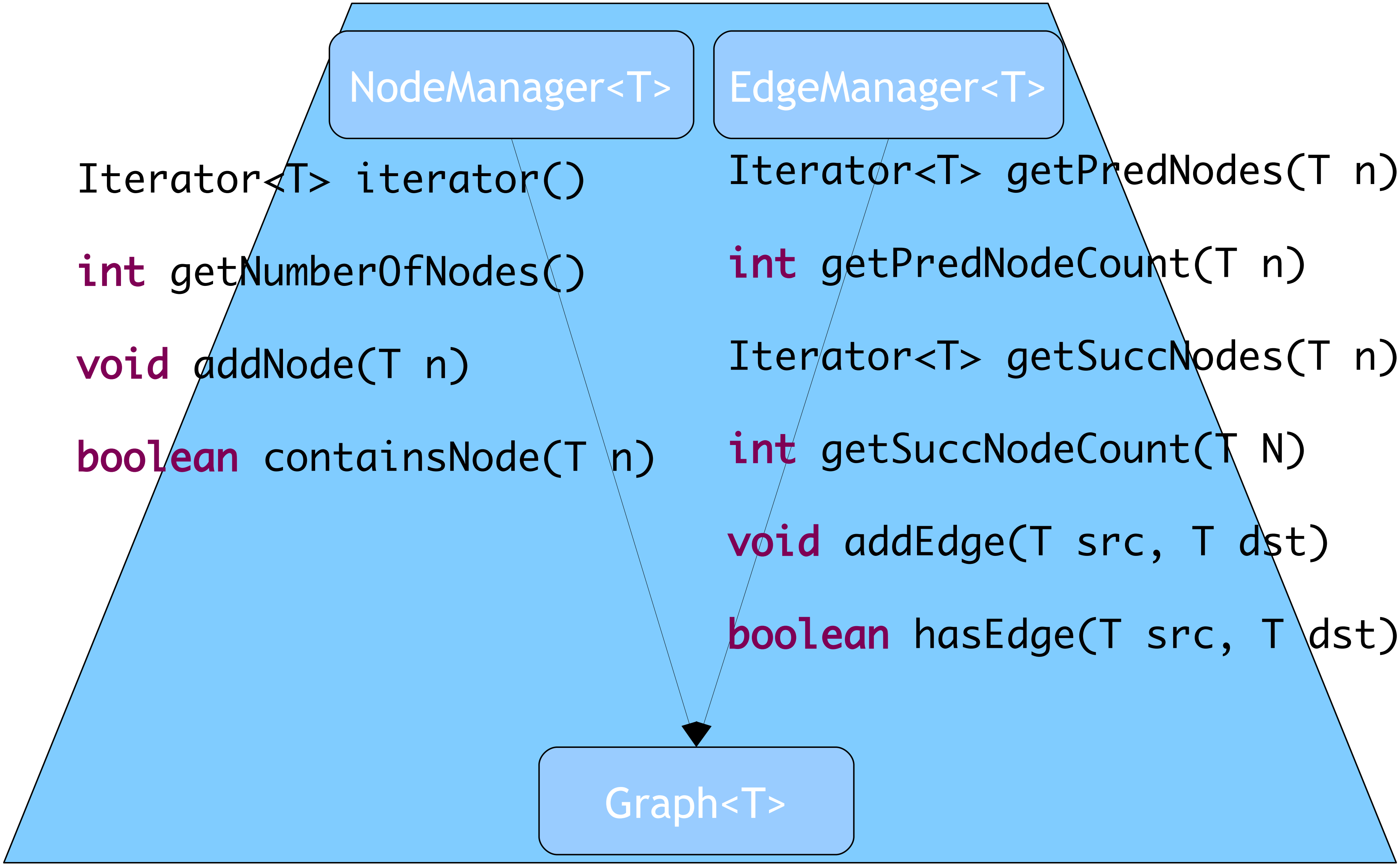
Debugging Bit Sets



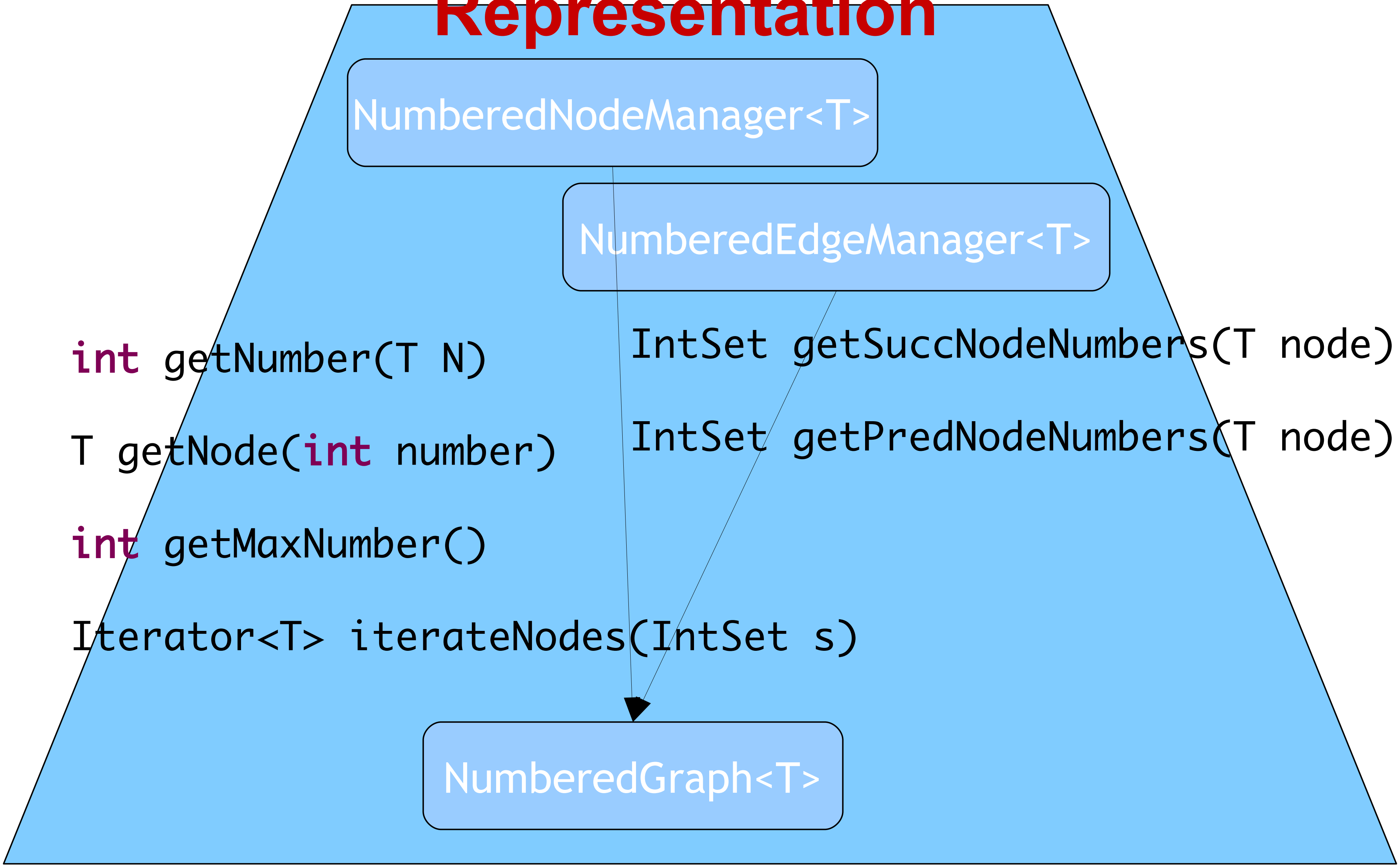

```java
public boolean add(int i) {
   boolean pr = left.add(i);
   boolean sr = right.add(i);

   if (pr != sr) {
     assert pr == sr;
   }

   return pr;
 }
```

- **Meant to help debug new bitset implementations**
  - **Parameterized by two other implementations**
  - **Assert two implementations give same results**
  - **Factory interface allows use as standard bitsets**
  - **For development only: major time and space costs**

Basic Graph Representation



Numbered Graph Representation




```
int getNumber(T N)

T getNode(int number)

int getMaxNumber()

Iterator<T> iterateNodes(IntSet s)

IntSet getSuccNodeNumbers(T node)

IntSet getPredNodeNumbers(T node)
```

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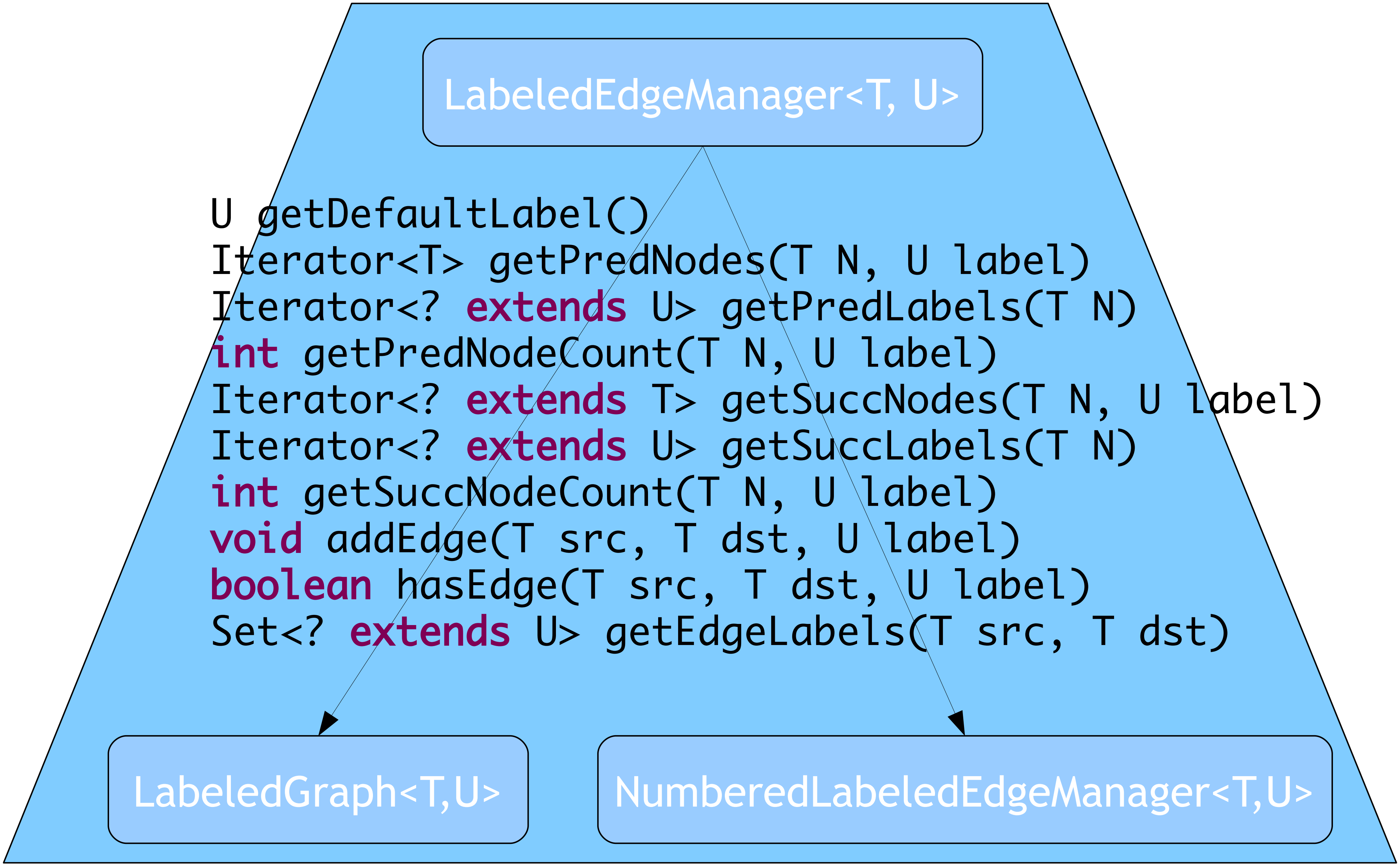
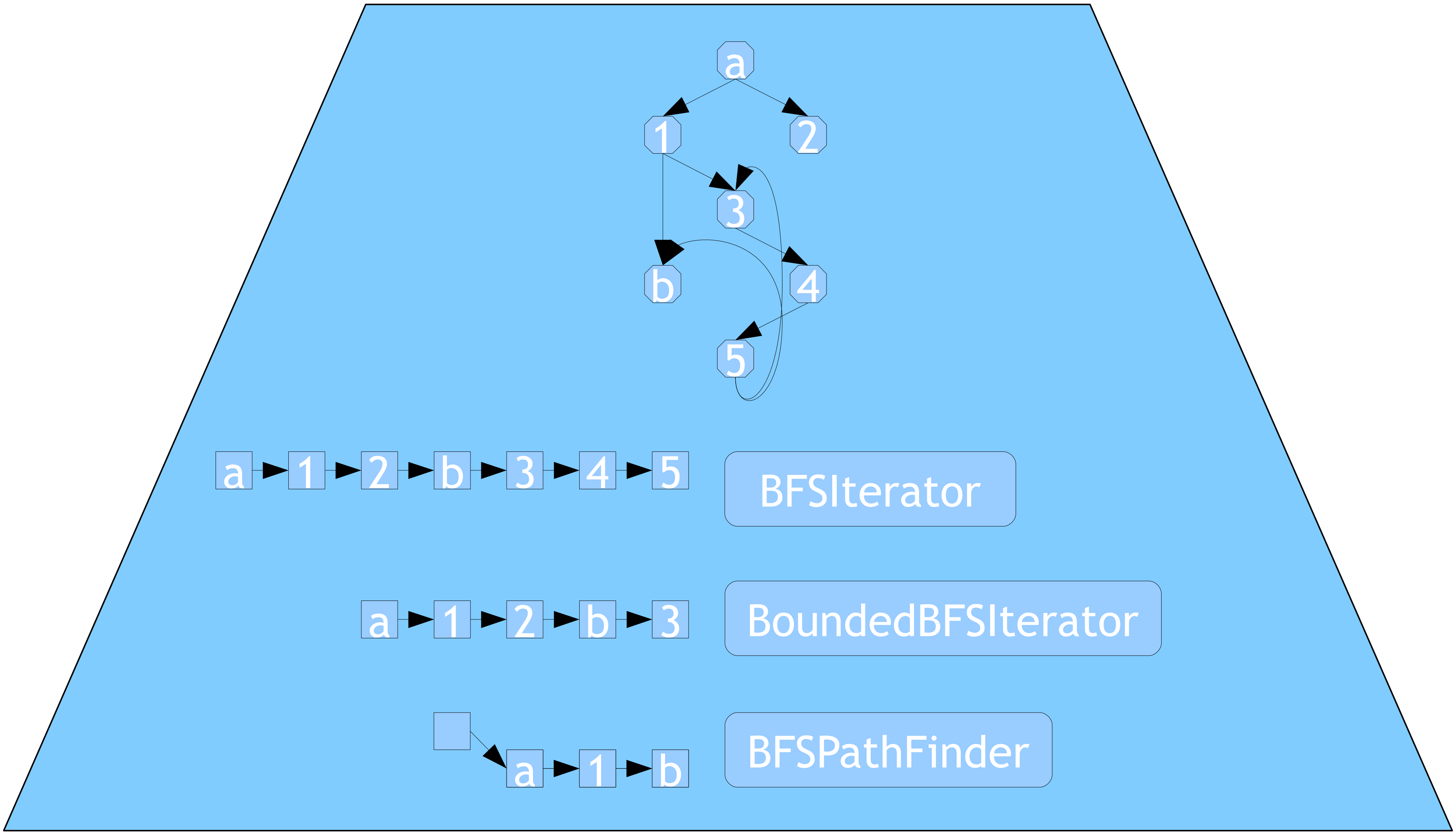
Labeled Graph Representation

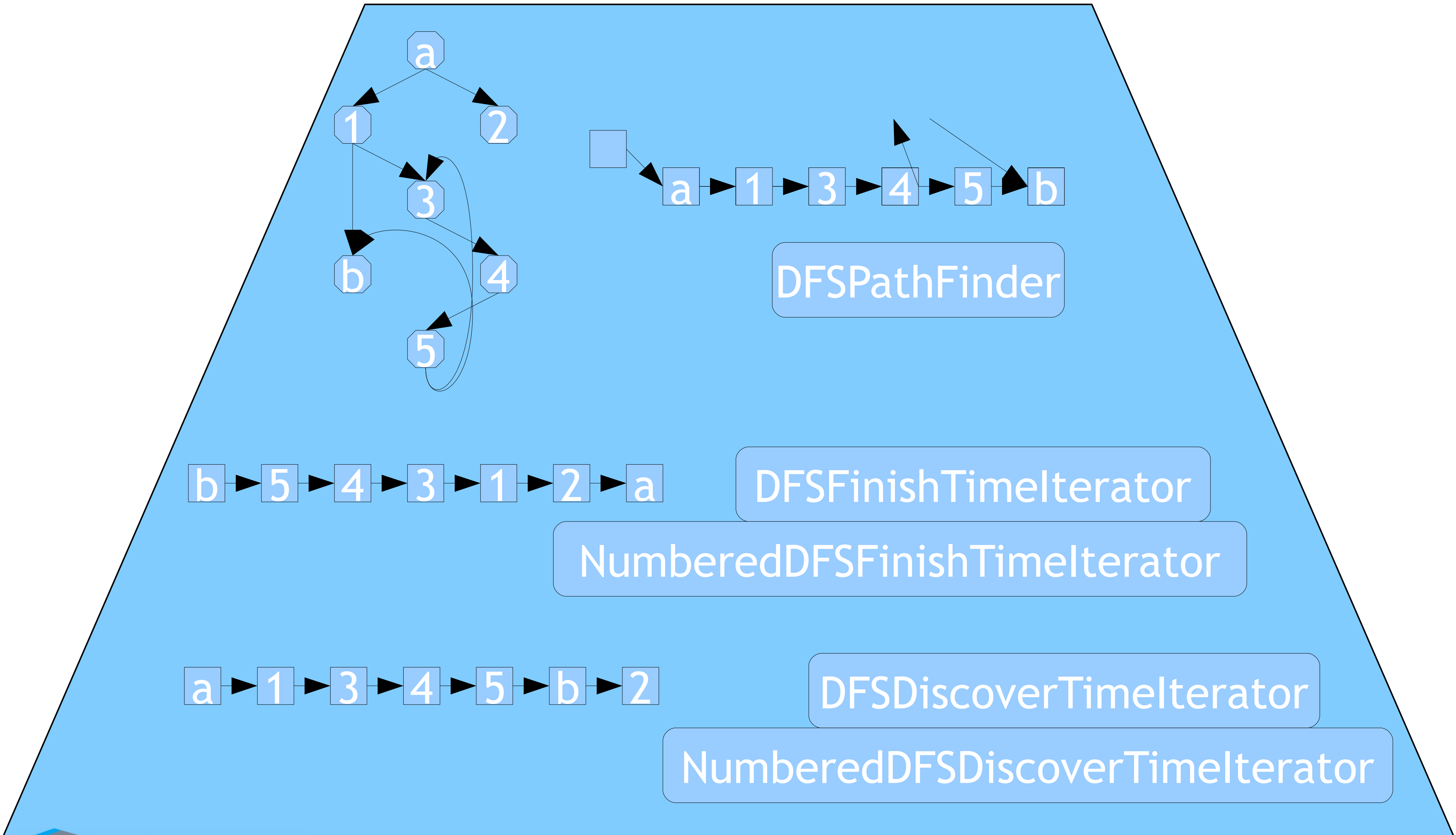



```
U getDefaultLabel()
Iterator<T> getPredNodes(T N, U label)
Iterator<? extends U> getPredLabels(T N)
int getPredNodeCount(T N, U label)
Iterator<? extends T> getSuccNodes(T N, U label)
Iterator<? extends U> getSuccLabels(T N)
int getSuccNodeCount(T N, U label)
void addEdge(T src, T dst, U label)
boolean hasEdge(T src, T dst, U label)
Set<? extends U> getEdgeLabels(T src, T dst)
```

Generic Graph Operations: Breadth First Search



Generic Graph Operations: Depth First Search



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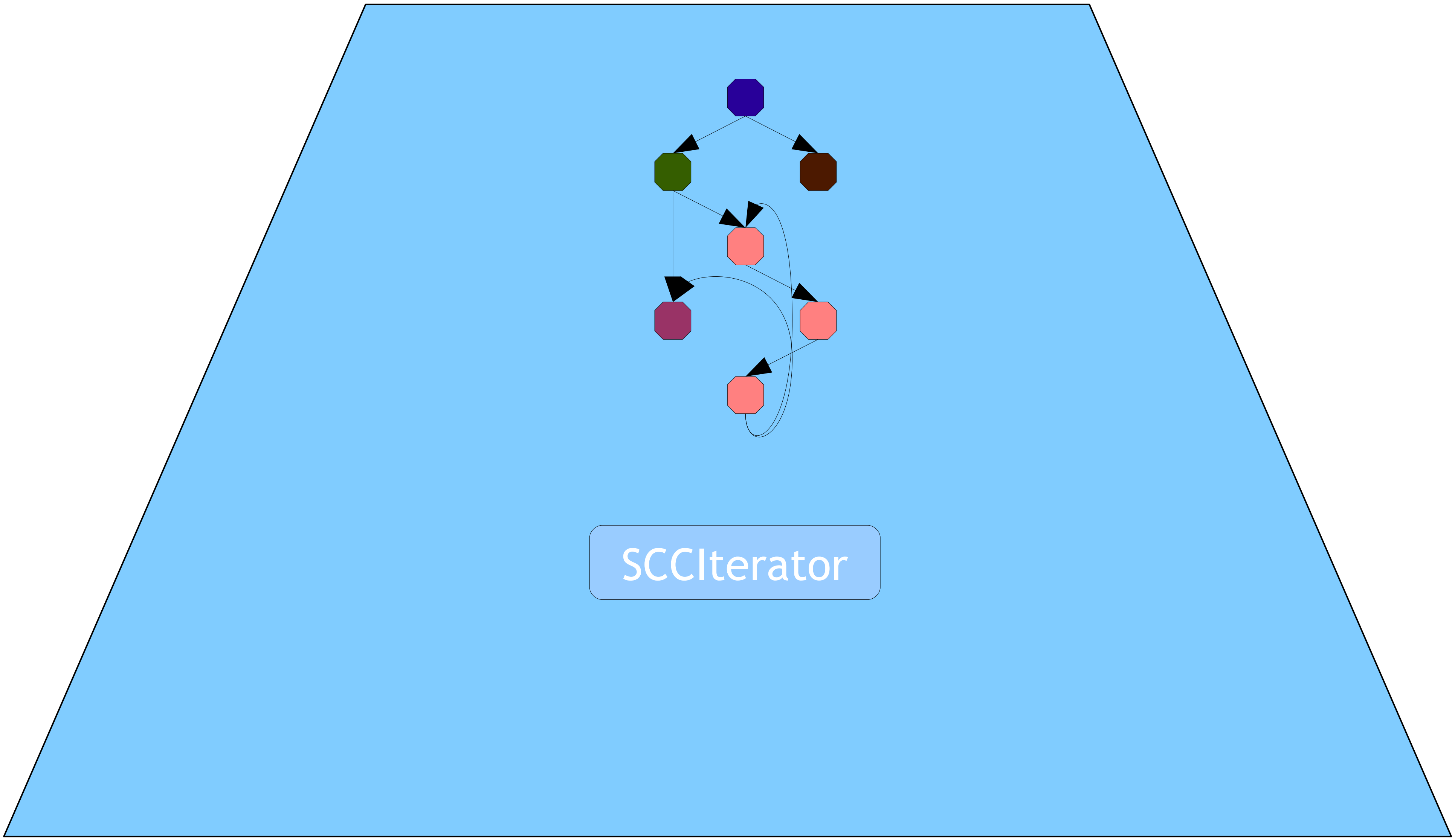
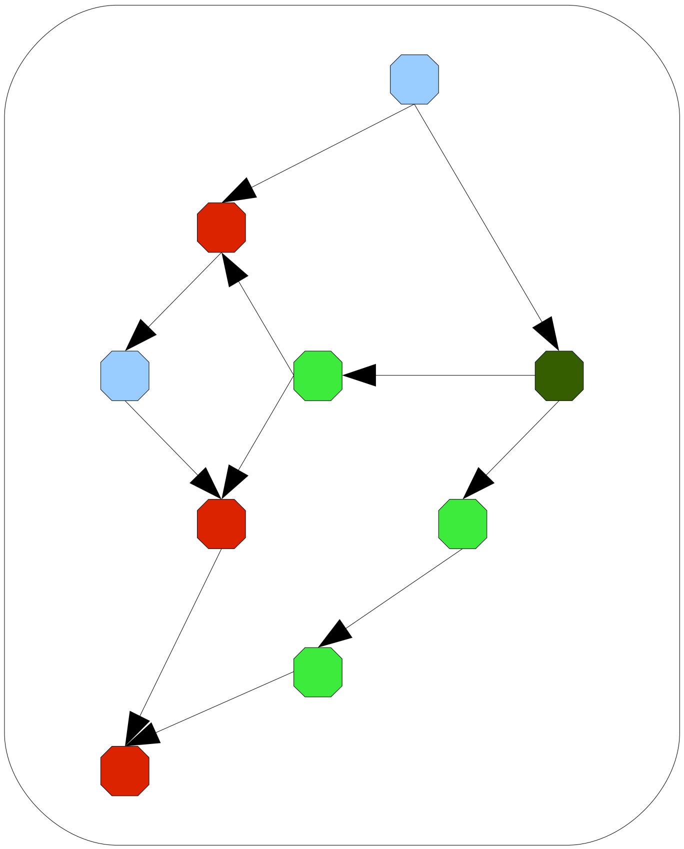
Generic Graph Operations: SCCs



Graph Algorithms



Dominators

NumberedDominators

DominanceFrontiers

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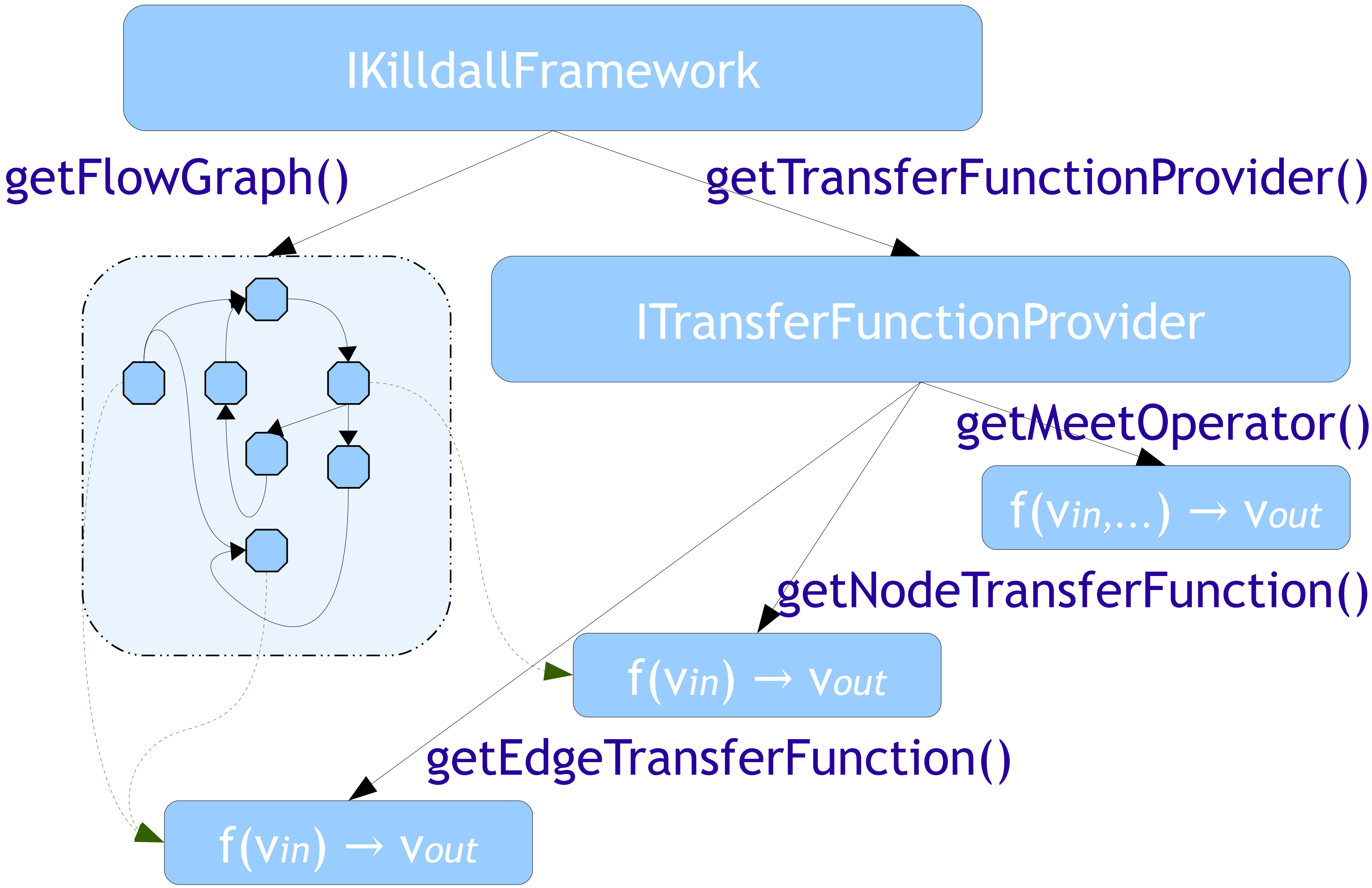
Dataflow Systems



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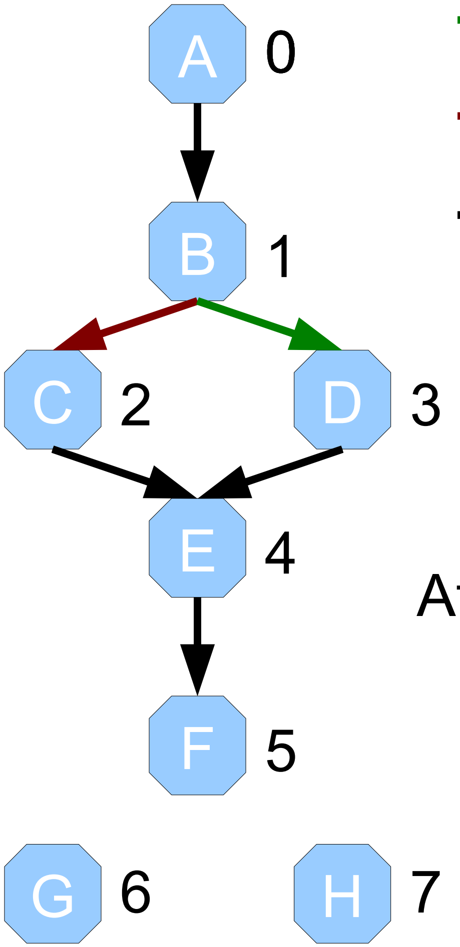
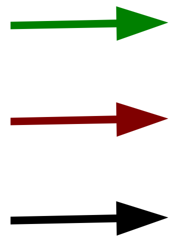
Dataflow Example





filters 0

filters 1

passes all values

At each node, transfer function adds its number

Example from GraphDataflowTest

Dataflow Example

```
public UnaryOperator<BitVectorVariable>
getNodeTransferFunction(String node) {
  return new BitVectorUnionConstant(
    values.getMappedIndex(node)); }

public UnaryOperator<BitVectorVariable>
getEdgeTransferFunction(String from, String to) {
  if (from == nodes[1] && to == nodes[3])
    return new BitVectorFilter(zero());
  else if (from == nodes[1] && to == nodes[2])
    return new BitVectorFilter(one());
  else {
    return BitVectorIdentity.instance();
}}

public AbstractMeetOperator<BitVectorVariable>
getMeetOperator() {
  return BitVectorUnion.instance(); }
```

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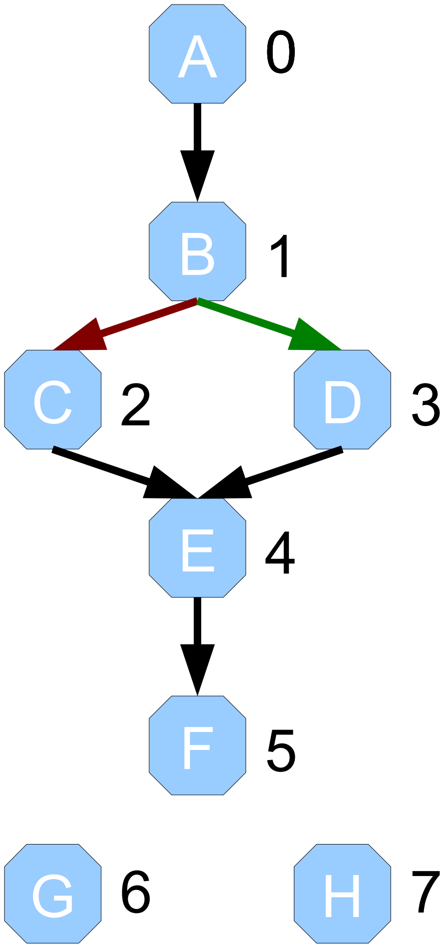
Dataflow Example




```
Node A(0) = { 0 }
Node B(1) = { 0 1 }
Node C(2) = { 0 2 }
Node D(3) = { 1 3 }
Node E(4) = { 0 1 2 3 4 }
Node F(5) = { 0 1 2 3 4 5 }
Node G(6) = { 6 }
Node H(7) = { 7 }
```

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INTERMEDIATE REPRESENTATION

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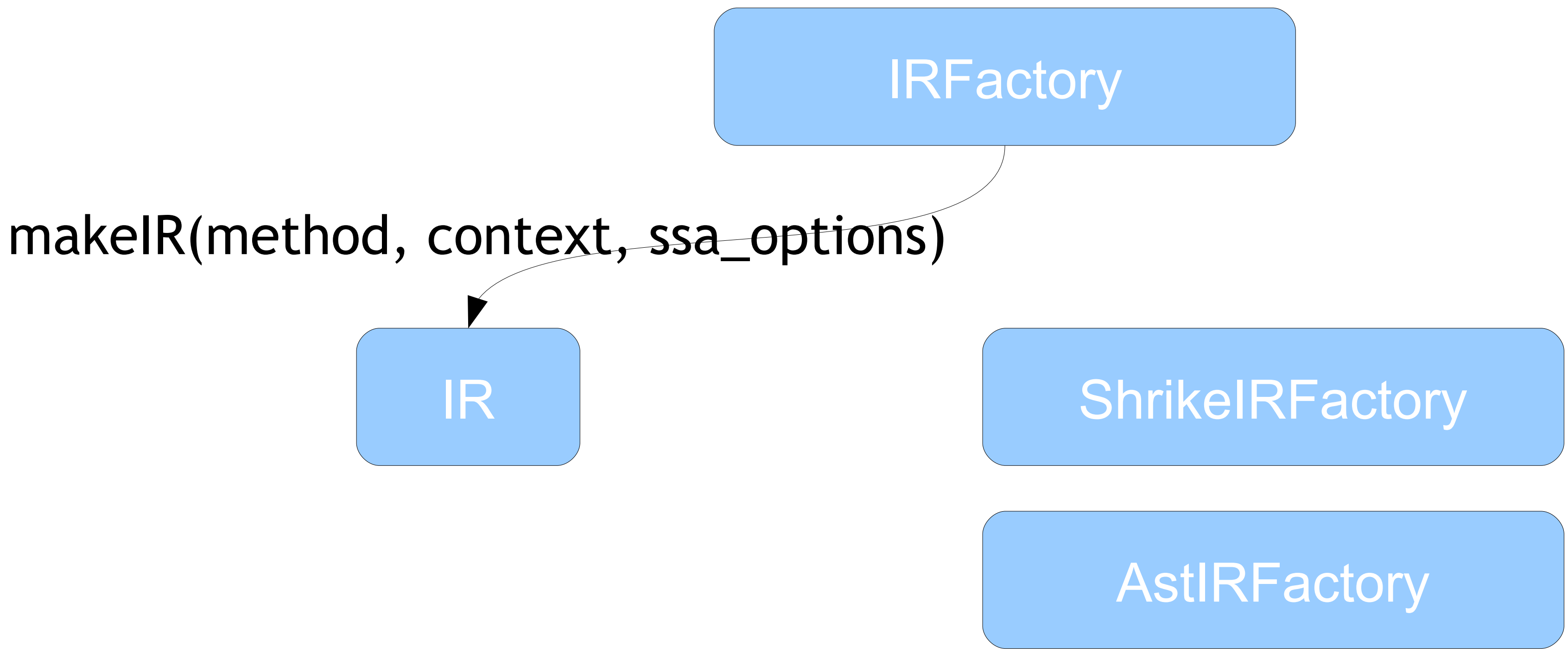
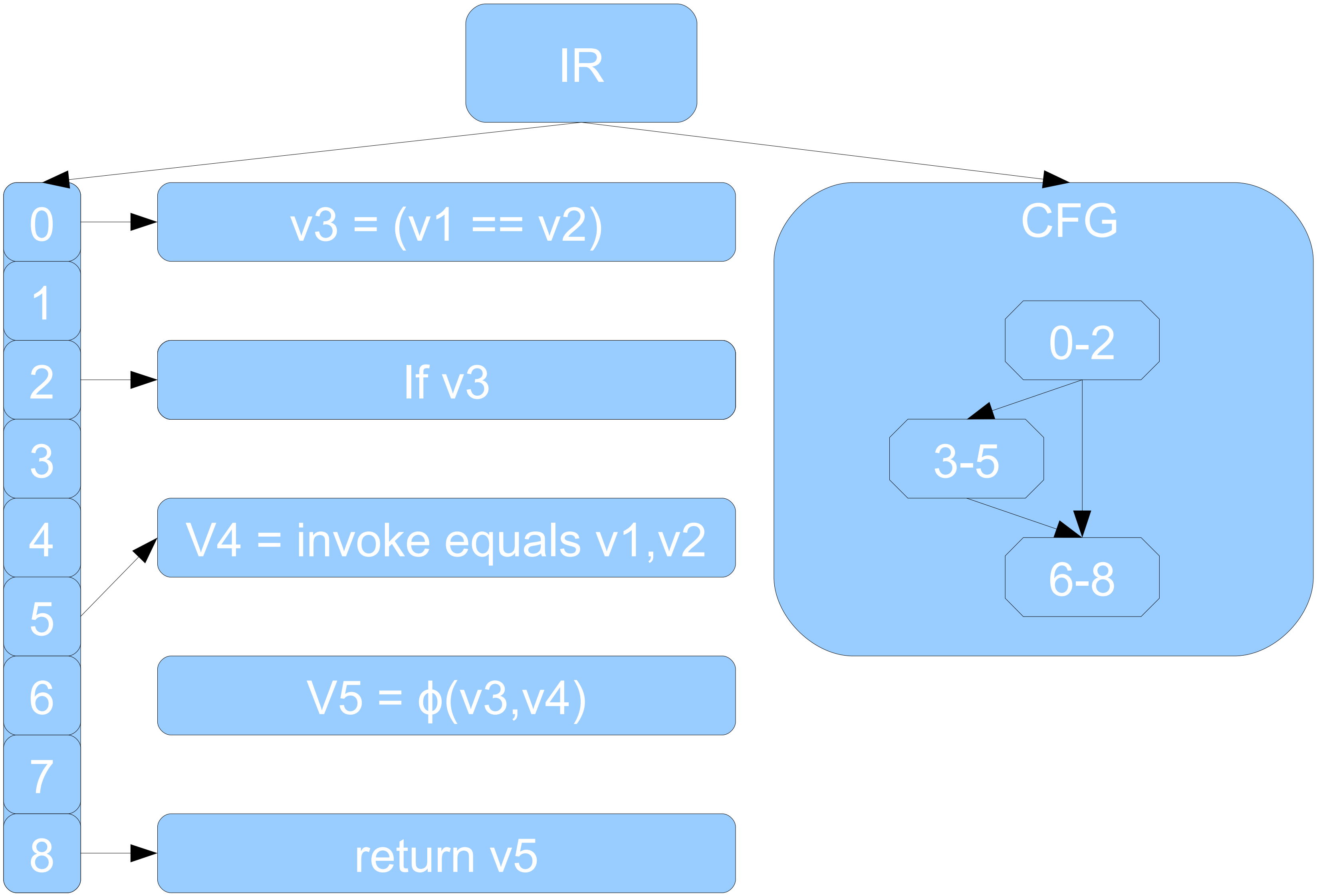
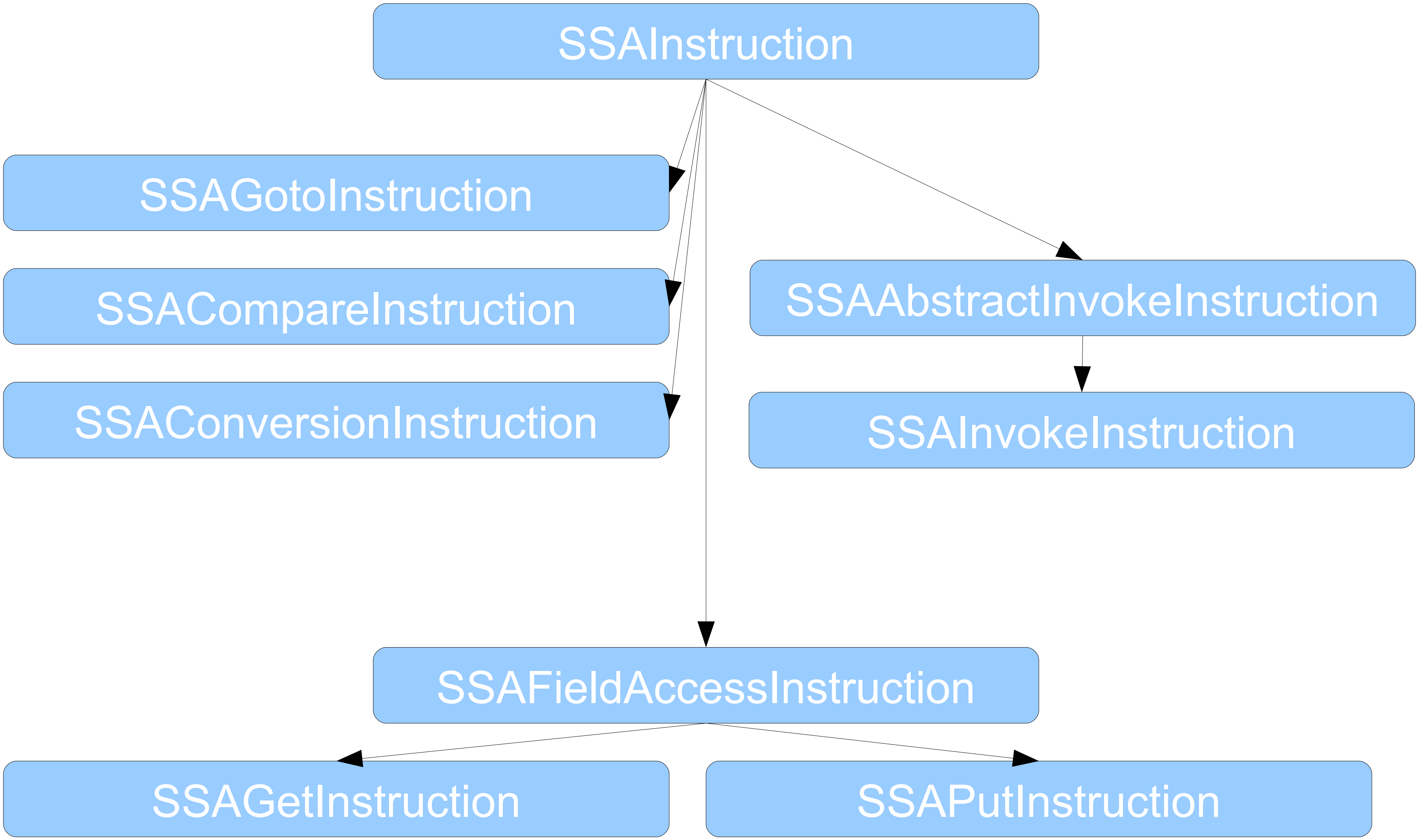
IR Factories



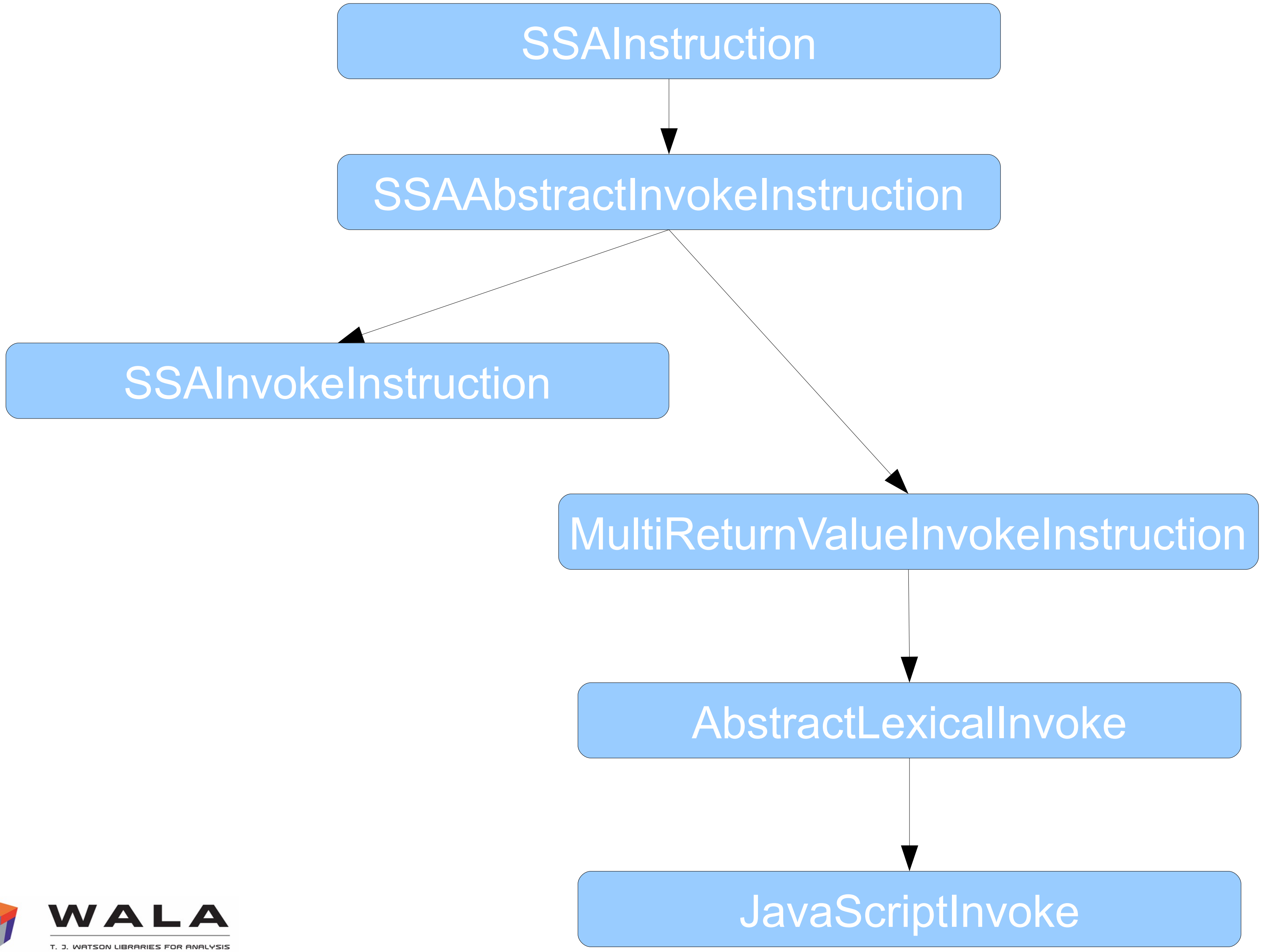
IR Structure



Instruction Types

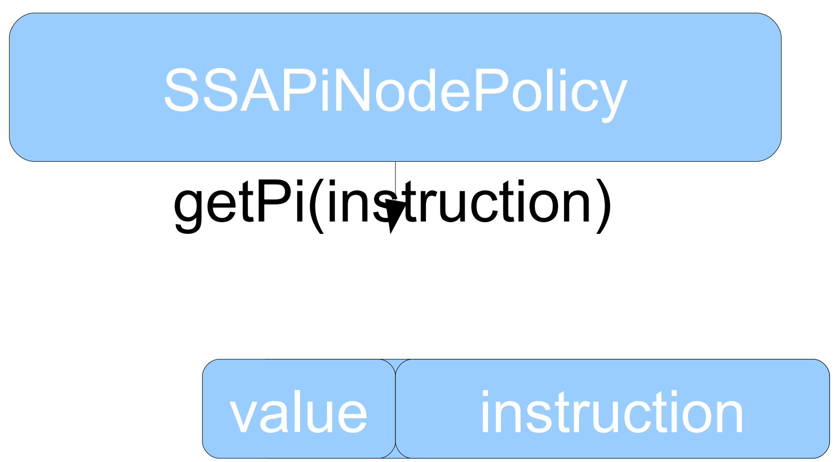


Instruction Types



IR Structure: Pi Nodes

- Pi nodes provide distinct value numbers in context
  - A “copy” of a value in a distinct context
  - e.g. inside a conditional or loop
- Used to denote precise information
  - e.g. aliasing with other values
  - e.g. precise type
- Specified by policy during IR creation



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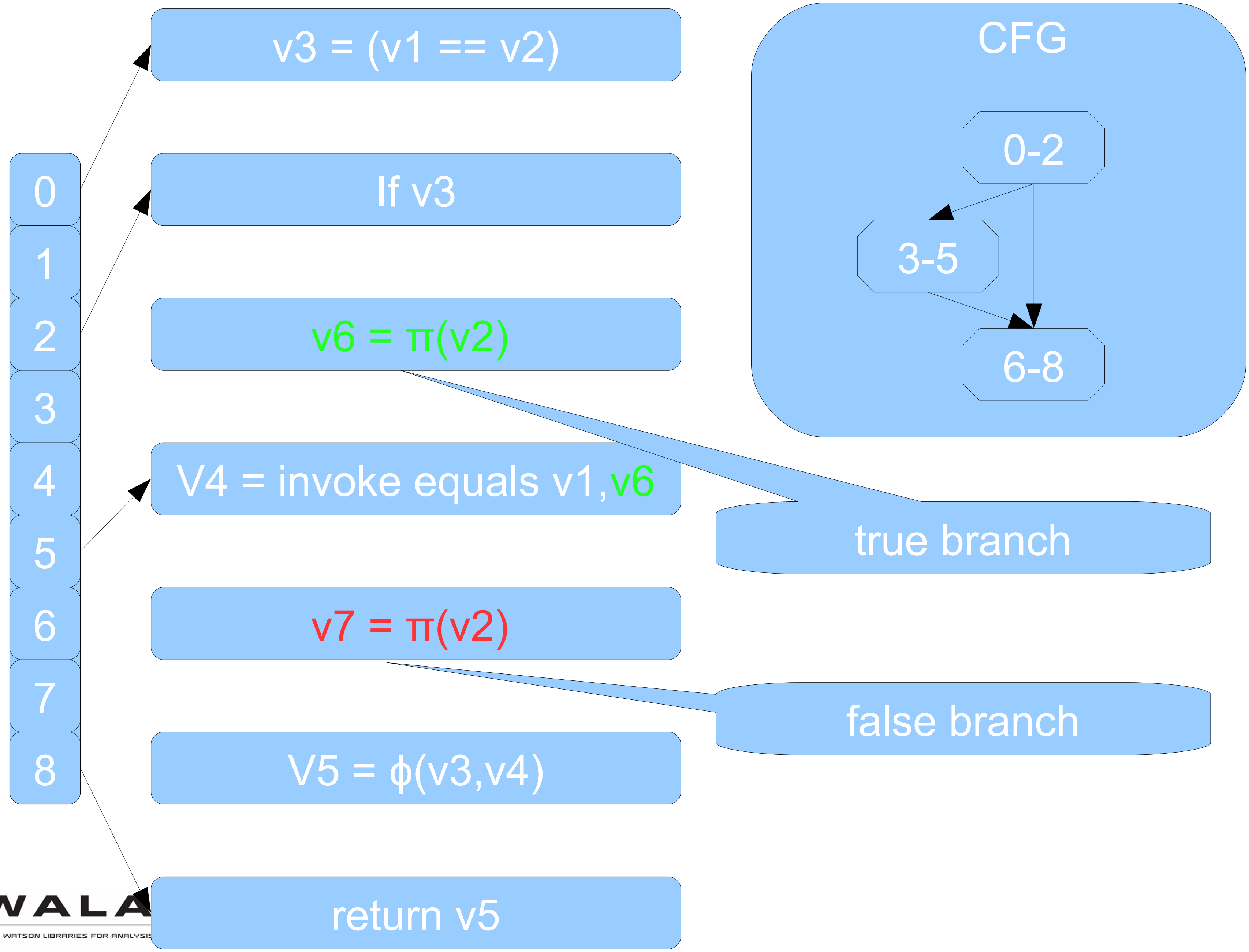
IR Structure: Pi Nodes



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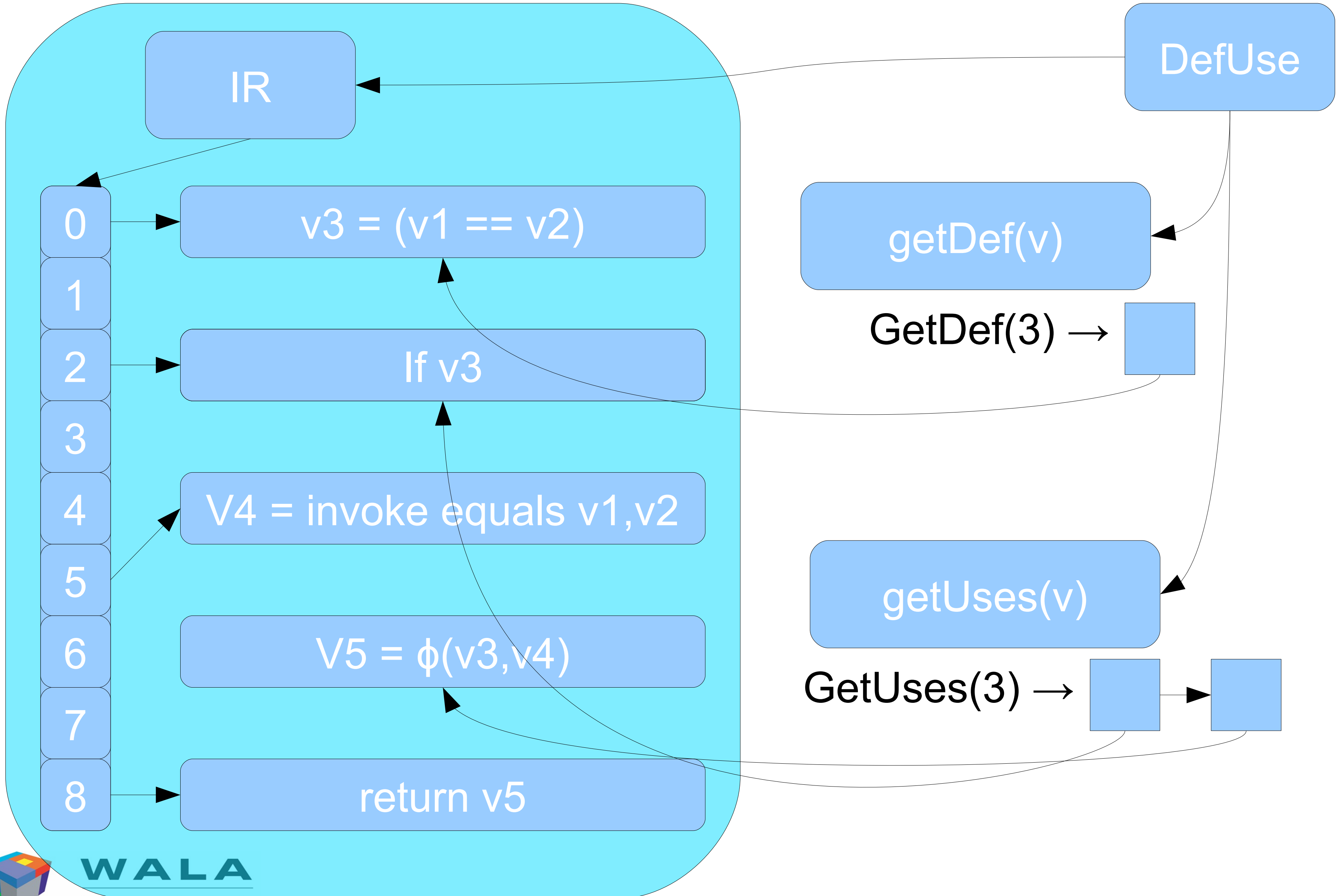
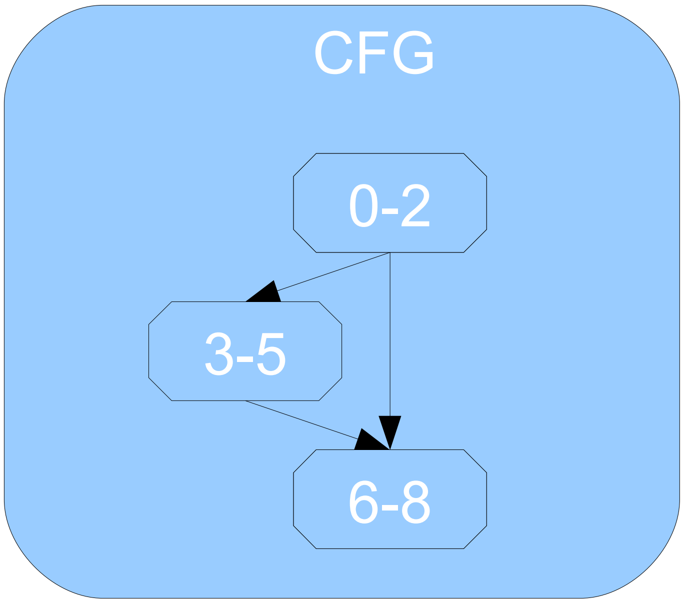
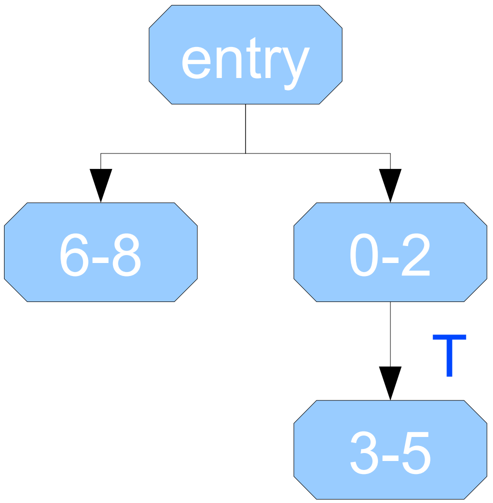
IR Utilities: DefUse



IR Utilities: CDG





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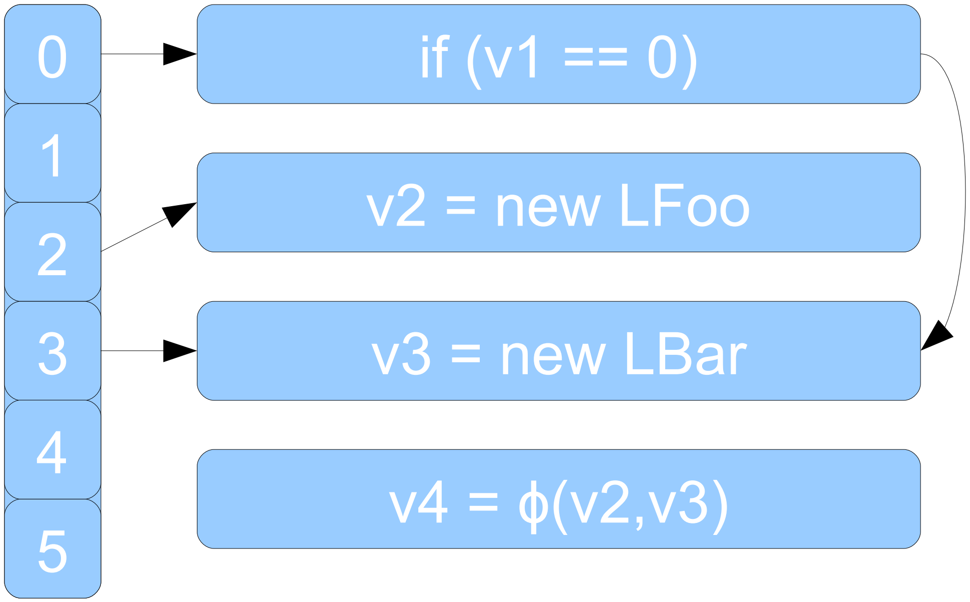
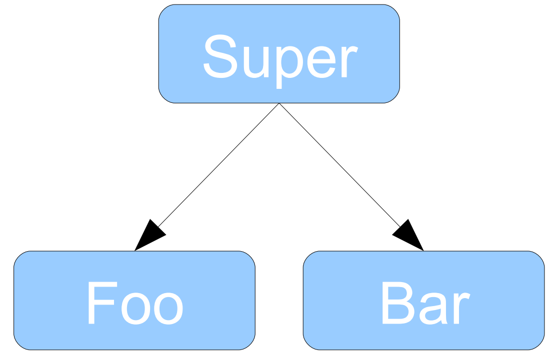
IR Utilities: Type Inference





v2=Foo, v3=Bar, v4=Super

Compute most precise 'most general type'

- **Uses declared types and other known types**
- **e.g. concrete types from constants**
- **e.g. concrete types from allocation**

Interface allows use across languages

```
new TypeInference(ir, doPrimitives); getType(vn)
```

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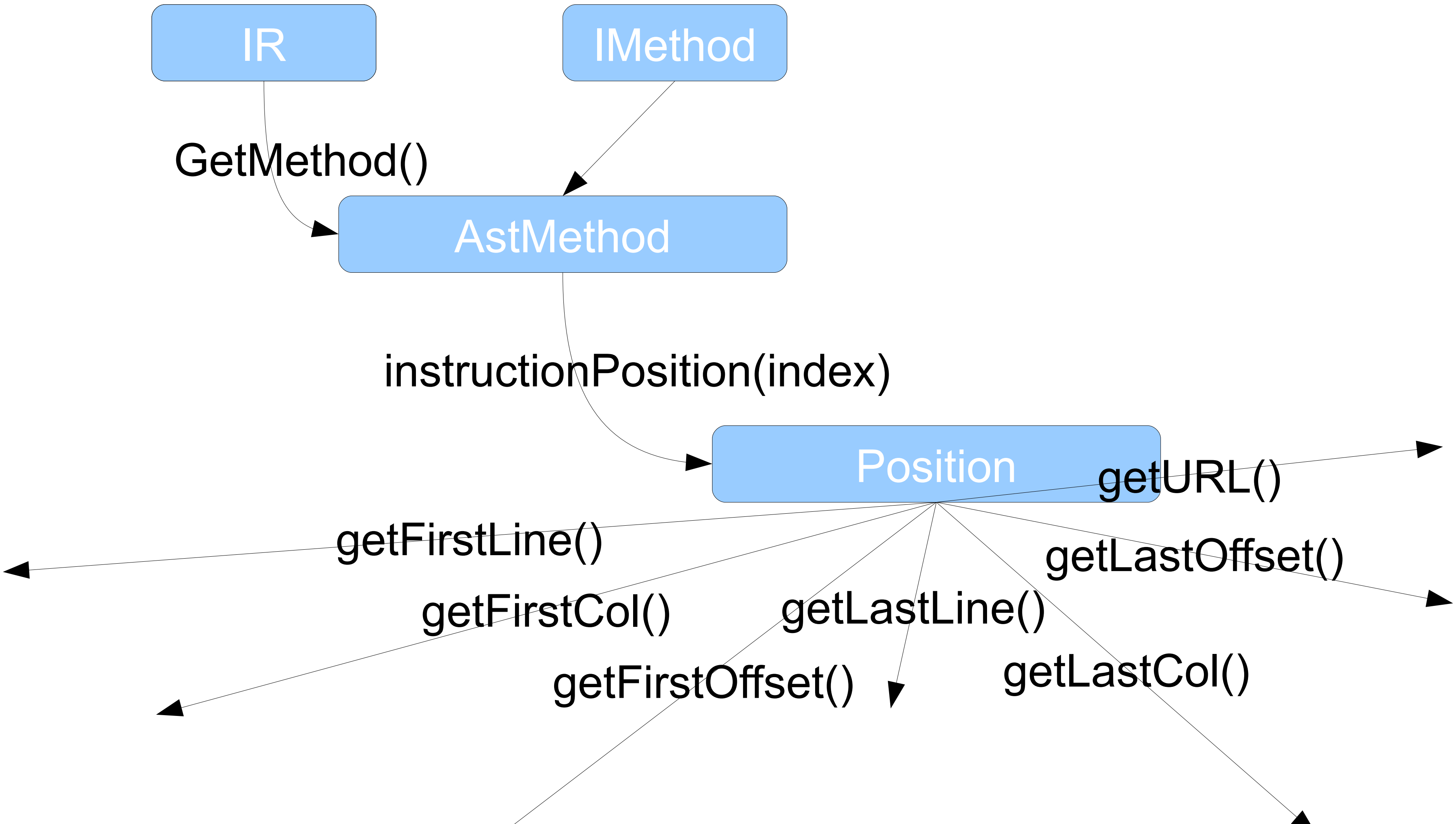
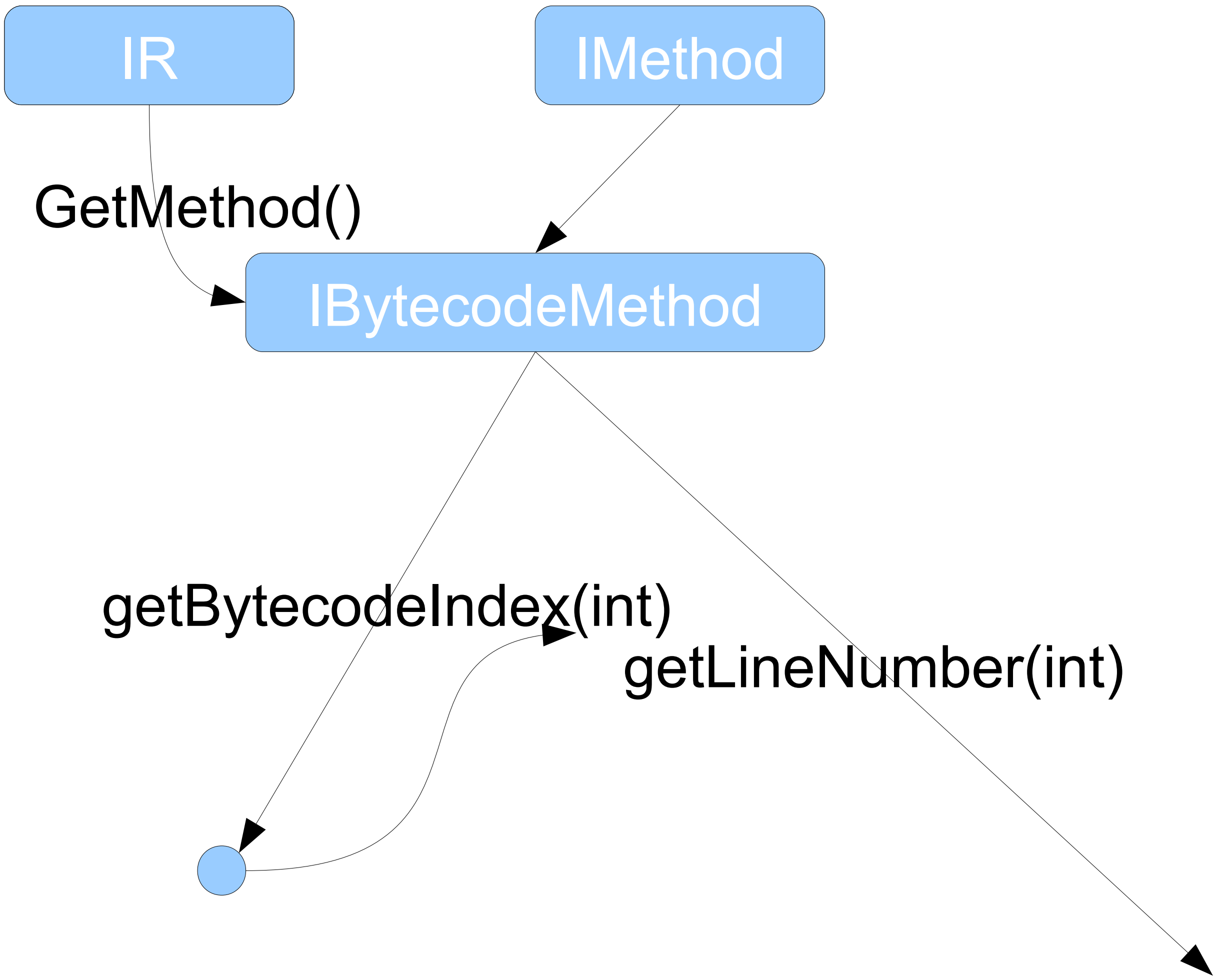
IR Source: CAst Source Map



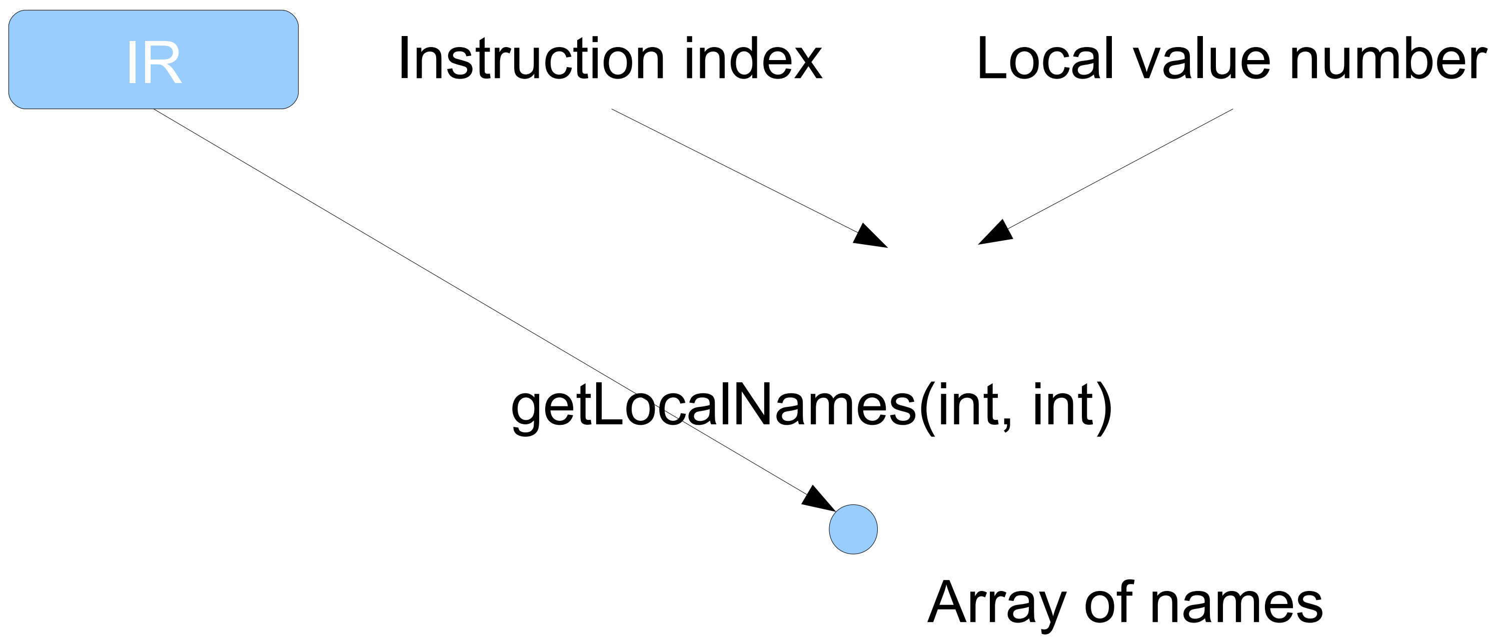
instructionPosition takes an offset in the instruction array

IR Source: Bytecode Map



GetBytecodeIndex takes an offset in the instruction array

IR Source: Local names



SCOPES AND CLASS HIERARCHIES

Building a Call Graph

```
buildCG(String jarFile) {
  // represents code to be analyzed
  AnalyisScope scope = AnalysisScopeReader                    (1)
      .makeJavaBinaryAnalysisScope(jarFile, null);
  // a class hierarchy for name resolution, etc.
  IClassHierarchy cha = ClassHierarchy.make(scope);           (2)
  // what are the call graph entrypoints?
  Iterable<Entrypoint> e =                                    (3)
      Util.makeMainEntrypoints(scope, cha);
  // encapsulates various analysis options
  AnalysisOptions o = new AnalysisOptions(scope, e);          (4)
  // builds call graph via pointer analysis
  CallGraphBuilder builder =                                  (5)
    Util.makeZeroCFABuilder(o, new AnalysisCache(),
                            cha, scope);
  CallGraph cg = builder.makeCallGraph(o, null);              (6)
}
```

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AnalysisScope

- Represents a set of files to analyze
- To construct from classpath:
  `AnalysisScopeReader.makeJavaBinaryAnalysisScope()`
- To read info from scope text file:
  `AnalysisScopeReader.readJavaScope()`
  - Each line of scope file gives loader, lang, type, val
    - E.g., “Application,Java,jarFile,bcel-5.2.jar”
    - Common types: classFile, sourceFile, binaryDir, jarFile
    - Examples in `com.ibm.wala.core.tests/dat`
- Exclusions: exclude some classes from consideration
  - Used to improve scalability of pointer analysis, etc.
  - Also specified in text file; see, e.g.,
    `com.ibm.wala.core.tests/dat/GUIExclusions.txt`

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Background: Class Loaders

- **In Java, a class is identified by name and class loader**
  - **E.g.,** `< Primordial, java.lang.Object >`
- **Class loaders form a tree, rooted at Primordial**
- **Name lookup first delegates to parent class loader**
  - **So, can’t write an app class** `java.lang.Object`
- **User-defined class loaders can provide isolation**
  - **Used by Eclipse for plugins, J2EE app servers**
- **WALA naming models class loaders**

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Multiple Names in Bytecode

```java
// this is java.lang.Object
class Object {
  public String toString() { … }
}
// no overriding of toString()
class B extends Object {}
class A extends B {}
```

Legal names in bytecode:

```
<Application, A, toString()>,
<Application, B, toString()>,
<Application, java.lang.Object, toString()>,
<Primordial, java.lang.Object, toString()>
```

Resolved entity:

```
<Primordial, java.lang.Object, toString()>
```

WALA Name Resolution

Entity references resolved via `IClassHierarchy`

Entity	Reference Type	Resolved Type	Resolver Method
class	TypeReference	IClass	`lookupClass()`
method	MethodReference	IMethod	`resolveMethod()`
Field	FieldReference	IField	`resolveField()`

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More on class hierarchies

- For Java class hierarchy: `ClassHierarchy.make(scope)`
- Supports Java-style subtyping (single inheritance, multiple interfaces)
- Necessary for constructing method IRs, since only resolved `IMethods` have bytecode info
- Watch out for memory leaks!
  - Resolved entities (`IClass`, `IMethod`, etc.) keep pointers back to class hierarchy
  - In general, use entity references in analysis results

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INTERPROCEDURAL DATAFLOW ANALYSIS

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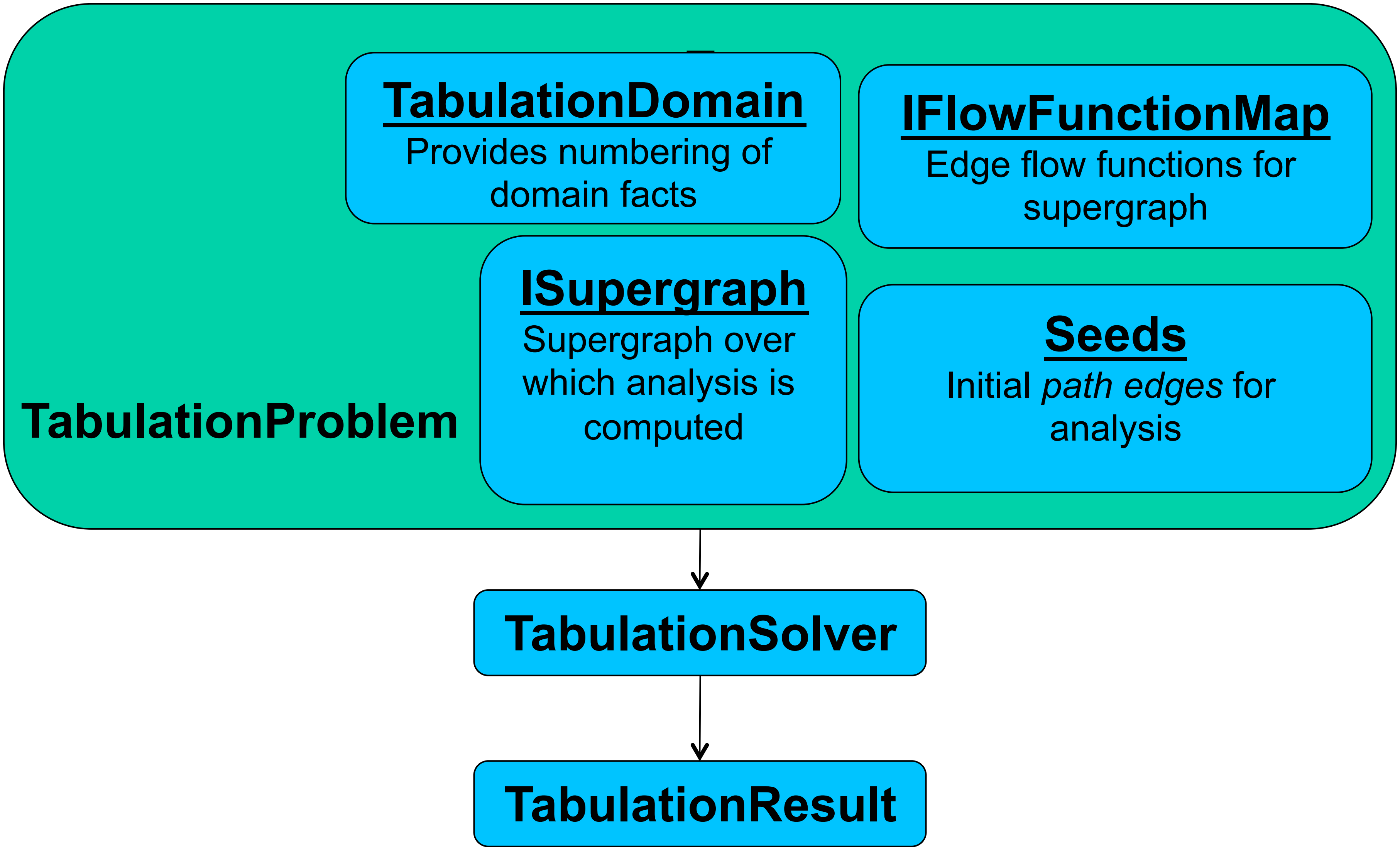
Tabulation-Based Analysis
(Reps, Horwitz, Sagiv, POPL95)

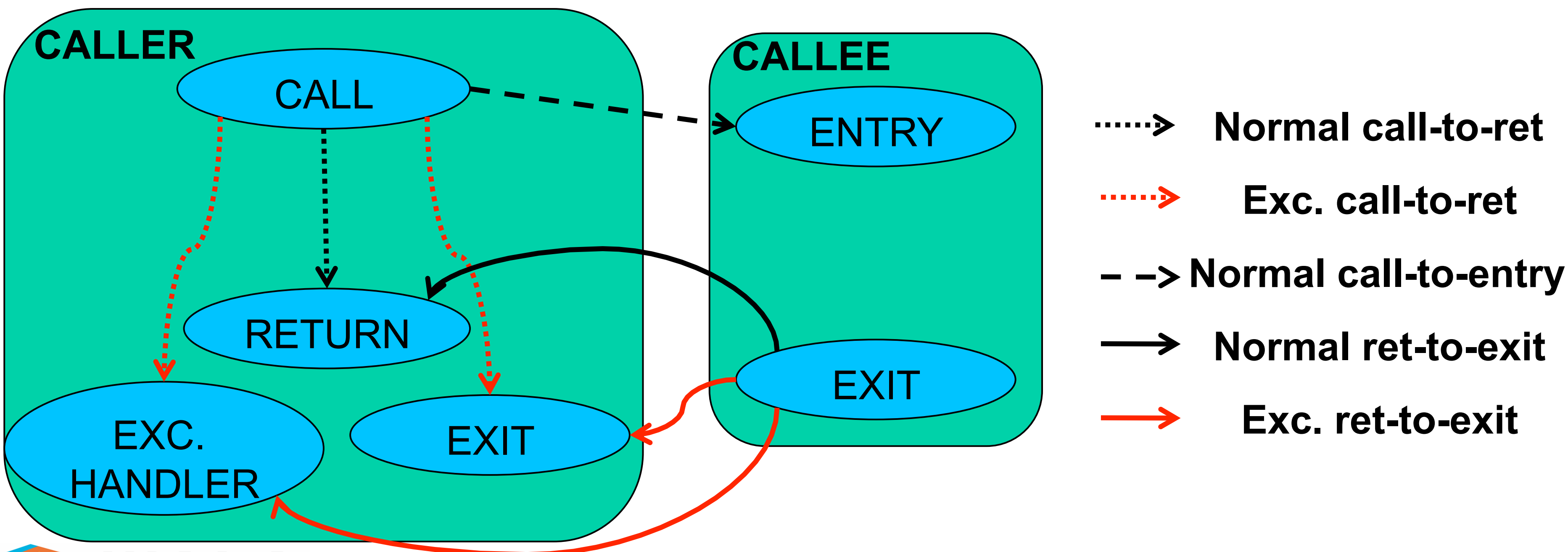
- "Functional approach" to context-sensitive analysis (Sharir and Pnueli, 1981)
- Tabulates partial function summaries on demand
- Some enhancements in WALA's implementation
  - Multiple return sites for calls (for exceptions)
  - Optional merge operators
  - Handles partially balanced problems
  - Customizable worklist orderings

Tabulation Overview



Supergraph

- Collection of "procedure graphs," connected by calls
  - `ICFGSupergraph`: procedure graphs are CFGs
  - `SDGSupergraph`: procedure graphs are PDGs
- <u>Example call representation for `ICFGSupergraph`</u>
  - (For general supergraph , possibly many calls, returns, entries, exits)



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Domain / Flow Functions / Seeds

- `TabulationDomain`
  - Maintains mapping from facts to integers
  - Controls worklist priorities (optional)
- `IFlowFunctionMap`
  - Flow functions on supergraph edges
  - All functions map `int` (or two `int`s) to `IntSet` (via `TabulationDomain`)
  - Function for each type of edge (normal, call->return, call->entry, exit->return)
  - Also, call->return function for “missing” calls
    - For handling missing code, CG expansion (Snugglebug)
- Seeds (`TabulationProblem.initialSeeds()`)
  - Depends on problem / domain representation

Partially Balanced Problems

- For when flows can start / end in a non-entrypoint
  - E.g., slice from non-entrypoint statement
- `PartiallyBalancedTabulationProblem`
  - Additional "unbalanced" return flow function for return without a call
  - `getFakeEntry()`: source node for path edges of partially balanced flows
- Compute with `PartiallyBalancedTabulationSolver`
- Examples: `ContextSensitiveReachingDefs, Slicer`

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Debugging Your Analysis

- `IFDSExplorer`
  - Gives GUI view of analysis result
  - Needs paths to GraphViz `dot` executable and PDF viewer
- Set VM property `com.ibm.wala.fixedpoint.impl.verbose` to true for occasional lightweight info
- Increase `TabulationSolver.DEBUG_LEVEL` for detailed info

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Deep Dive: Reaching Defs

- The classic dataflow analysis, for Java static fields
- Three implementations available in `com.ibm.wala.core.tests`
  - `IntraprocReachingDefs`
    - Uses `BitVectorSolver`, a specialized `DataflowSolver`
  - `ContextInsensitiveReachingDefs`
    - Uses `BitVectorSolver` over interprocedural CFG
  - `ContextSensitiveReachingDefs`
    - Uses `TabulationSolver`
- We'll focus on `ContextSensitiveReachingDefs`

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Example

```
class StaticDataflow {
  static int f, g;
  static void m() { f = 2; }
  static void testInterproc() {
    f = 3;
    m();                                    (1)
    g = 4;
    m();                                    (2)
  }
}
```

Context-*sensitive* analysis should give different result after *(1)* and *(2)*

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The Domain and Supergraph

- **Supergraph: ICFGSupergraph**
  - **<u>Procedures</u>: call graph nodes (CGNode)**
    - **In context-sensitive call graph, possibly many CGNodes for one Imethod**
  - **<u>Nodes</u>: BasicBlockInContext<IExplodedBasicBlock>**
    - **"exploded" basic block has at most one instruction (eases writing transfer functions)**
    - **BasicBlockInContext pairs BB with enclosing CGNode**
- **Domain (static field writes): Pair<CGNode,Integer>**
  - **Integer is index in IR instruction array; only valid way to uniquely identify IR instruction**
  - **ReachingDefsDomain extends MutableMapping to maintain fact numbering**

Flow Functions (1)

- Normal flow for non-putstatics is `IdentityFlowFunction.identity()`
- Most call-related flow functions are also identity
  - Since static fields are in global scope
- Call-to-return function is `KillEverything.singleton()`
  - Defs must survive callee to reach return

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Flow Functions (2)

Normal flow function for putstatic

(modified for formatting / clarity)

```
public IntSet getTargets(int d1) {
  IntSet result = MutableSparseIntSet.makeEmpty();
  // first, gen this statement
  int factNum = domain.getMappedIndex(Pair.make(node, index));
  result.add(factNum);
  // if incoming statement defs the same static field, kill it;
  // otherwise, keep it
  if (d1 != factNum) { // must be different statement
    IField sf = cha.resolveField(putInstr.getField());
    Pair<CGNode, Integer> other = domain.getMappedObject(d1);
    SSAPutInstruction otherPut = getPutInstr(other);
    IField otherSF = cha.resolveField(otherPut.getField());
    if (!sf.equals(otherSF)) { result.add(d1); }
  }
  return result;
}
```

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Seeds

- **Standard tabulation approach: special ‘0’ fact**
  - **Add ‘0 -> 0’ edge to all flow functions**
  - **Seed with (main_entry, 0) -> (main_entry, 0)**
- **Our approach: partially balanced tabulation**
  - **For field write numbered *n* in basic block *b of* method *m*, add seed (*m_entry*, *n*) -> (*b, n*)**
    - **(source fact doesn’t matter)**
  - **Unbalanced flow function is just identity**
  - **Advantage: keeps other flow functions cleaner**
  - **See `ReachingDefsProblem.collectInitialSeeds()`**

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Putting it all Together

- `ReachingDefsProblem` **collects domain, supergraph, flow functions, seeds**
- **Running analysis (simplified):**

```
PartiallyBalancedTabulationSolver solver =
  new PartiallyBalancedTabulationSolver(
    new ReachingDefsProblem());
TabulationResult result = solver.solve();
```

- **In the real code:**
  - **Lots of long generic type instantiations (sigh)**
  - **Handling `CancelException` (enables cancelling running analysis from GUI)**

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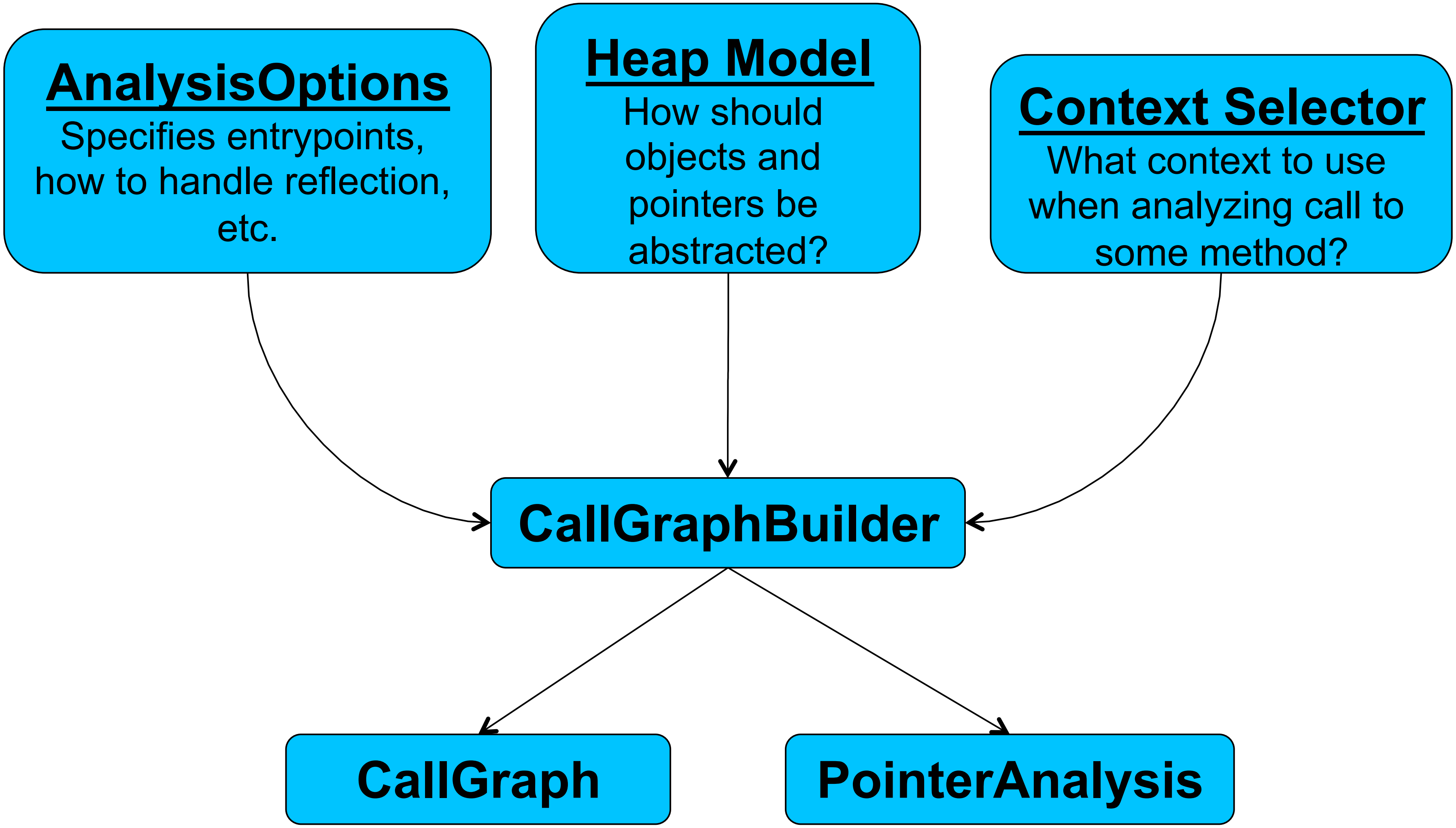
CALL GRAPHS / POINTER ANALYSIS

Call Graph Builder Overview



Entrypoints

- What are entrypoint methods?
  - `main()` method
    - `Util.makeMainEntrypoints()`
  - All application methods
    - `AllApplicationEntrypoints`
  - JavaEE Servlet methods, Eclipse plugin entries, …
- What types are passed to entrypoint arguments?
  - Just declared parameter types (`DefaultEntrypoint`)
  - Some concrete subtype (`ArgumentTypeEntrypoint`)
  - All subtypes (`SubtypesEntrypoint`)

Heap Model

- Controls abstraction of pointers and object instances
- `InstanceKey`: abstraction of an object
  - All objects of some type (`ConcreteTypeKey`)
  - Objects allocated by some statement in some calling context (`AllocationSiteInNode`)
  - `ZeroXInstanceKeys`: customizable factory
- `PointerKey`: abstraction of a pointer
  - Local variable in some calling context (`LocalPointerKey`)
  - Several merged vars (offline substitution), etc.

Context Selector

- Gives context to use for callee method at some call site
- `Context` examples
  - The default context (`Everywhere`)
  - A call string (`CallStringContext`)
  - Receiver object (`ReceiverInstanceContext`)
- `ContextSelector` examples
  - `nCFAContextSelector`: n-level call strings
  - `ContainerContextSelector`: object sensitivity for containers

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Built-In Algorithms

(Grove and Chambers, TOPLAS 2001)

Rapid Type Analysis (RTA)

<u>0-CFA</u>
context-insensitive, class-based heap

<u>0-1-CFA</u>
context-insensitive, allocation-site-based heap

<u>0-1-Container-CFA</u>
0-1-CFA with object-sensitive containers

Increasing precision ↓

For builders, see `com.ibm.wala.ipa.callgraph.impl.Util`

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Performance Tips

- **Use AnalyisScope exclusions**
  - **Often, much of standard library (e.g., GUI libraries) is irrelevant**
- **Analyze older libraries**
  - **Java 1.4 libraries much smaller than Java 6**
- **Tune context-sensitivity policy**
  - **E.g., more sensitivity just for containers**

Code Modelling (Advanced)

- `SSAContextInterpreter`: builds SSA for a method
  - Normally, based on bytecode
  - Customized for reflection, `Object.clone()`, etc.
- `MethodTargetSelector`: determines method dispatch
  - Normally, based on types / class hierarchy
  - Customized for native methods, JavaEE, etc.
- `ClassTargetSelector`: determines types of allocated objects
  - Normally, type referenced in `new` expression
  - Customized for adding synthetic fields, JavaEE, etc.

Refinement-Based Points-To Analysis

- Refines analysis precision as requested by client
  - Computes results on demand
  - See Sridharan and Bodik, PLDI 2006
- Implemented in `DemandRefinementPointsTo`
  - Baseline analysis is context insensitive
    - Field sensitivity, on-the-fly call graph via refinement
  - Context sensitivity (modulo recursion), other regular properties via additional state machines
  - Refinement policy can be easily customized
  - Can also compute “flows to” on demand
- Usage fairly well documented on wiki
- See `DemandCastChecker` for an example client

SLICING

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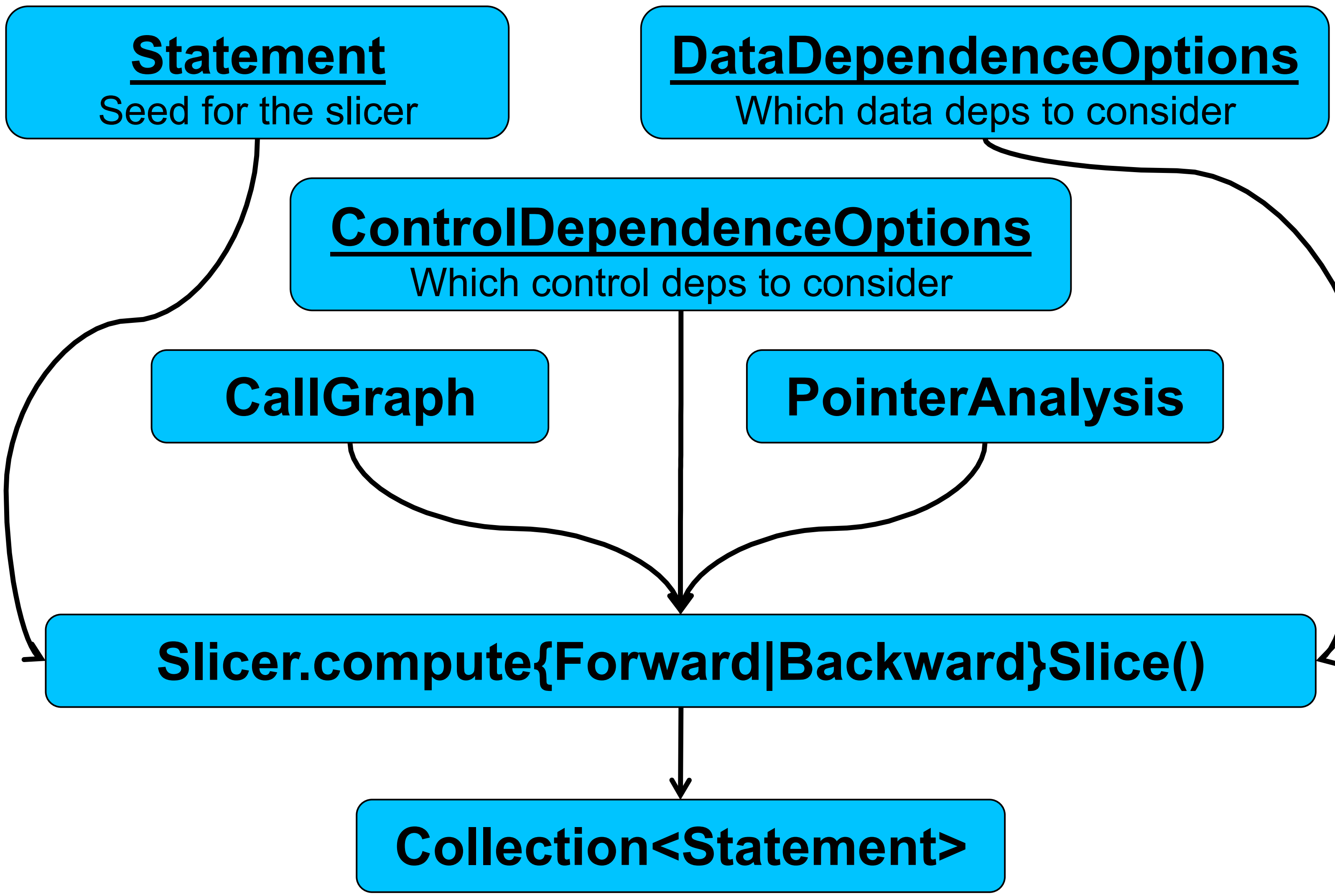
Slicer Overview



Statement

- Identifies a node in the System Dependence Graph (SDG) [Horwitz,Reps,Binkley,TOPLAS'90]
- Key statement types
  - `NormalStatement`
    - Normal SSA IR instruction
    - Represented by `CGNode` and instruction index
  - `ParamCaller, ParamCallee`
    - Extra nodes for modeling parameter passing
    - SDG edges from def -> `ParamCaller` -> `ParamCallee` -> use
  - `NormalReturnCaller, NormalReturnCallee`
    - Analogous to `ParamCaller, ParamCallee`
    - Also `ExceptionalReturnCaller/Callee`
  - `HeapParamCaller, HeapParamCallee`, etc.
    - For modeling interprocedural heap-based data deps
    - Edges via interprocedural mod-ref analysis

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Dependence Options

- `DataDependenceOptions`
  - `FULL` (all deps) and `NONE` (no deps)
  - `NO_BASE_PTRS`: ignore dependencies for memory access base pointers
    - E.g., exclude forward deps from defs of `x` to `y=x.f`
  - `NO_HEAP`: ignore dependencies to/from heap locs
  - `NO_EXCEPTIONS`: ignore deps from throw to catch
  - Various combinations (e.g., `NO_BASE_NO_HEAP`)
- `ControlDependenceOptions`
  - `FULL` (all deps) and `NONE` (no deps)
  - `NO_EXCEPTIONAL_EDGES`: ignore exceptional control flow

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Thin Slicing

- **Just "top-level" data dependencies (see [Sridharan-Fink-Bodik PLDI'07])**
- **For context-*sensitive* thin slicing, use `Slicer` with `DataDependenceOptions.NO_BASE_PTRS` and `ControlDependenceOptions.NONE`**
- **For efficient context-*insensitive* thin slicing, use the `CISlicer` class**

Performance Tips

- Some configs do not scale to large programs
  - E.g., context-sensitive slicing with heap deps
  - Discussion in [SFB07]
- Run with minimum dependencies needed
- Apply pointer analysis scalability tips
  - Exclusions, earlier Java libraries

INSTRUMENTING BYTECODES WITH SHRIKE

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Key Shrike Features

- Patch-based instrumentation API
  - Each instrumentation pass implemented as a patch
  - Several patches can be applied simultaneously to original bytecode
    - No worries about instrumenting the instrumentation
  - Branch targets / exc. handlers automatically updated
- Efficient
  - Unmodified class methods copied without parsing
  - Efficient bytecode representation / parsing
    - Array of immutable instruction objects
    - Constant instrs represented with single shared object
- Some ugliness hidden
  - JSRs, exception handler ranges, 64k method limit

Key Shrike Classes

ShrikeCT: reading / writing .class files

- **ClassReader** — Immutable view of .class file info; reads data lazily
- **ClassWriter** — Generates JVM representation of a class

ShrikeBT: instrumenting bytecodes

- **MethodEditor** — Core class for transforming bytecodes via patches
- **ClassInstrumenter** — Utility for instrumenting an existing class (mutable)
- **MethodData** — Mutable view of method info
- **CTCompiler** — Compiles ShrikeBT method into JVM bytecodes

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Instrumenting A Method (1)

```
instrument(byte[] orig, int i) {
  // mutable helper class
  ClassInstrumenter ci =                              (1)
    new ClassInstrumenter(orig);
  // mutable representation of method data
  MethodData md = ci.visitMethod(i);                  (2)
  // see next slide; mutates md, ci
  doInstrumentation(md);                              (3)
  // output instrumented class in JVM format
  ClassWriter w = ci.emitClass();                     (4)
  byte[] modified = w.makeBytes();                    (5)
}
```

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Instrumenting A Method (2)

```
doInstrumentation(MethodData md) {
  // manages the patching process
  MethodEditor me = new MethodEditor(md);     (1)
  me.beginPass();                             (2)
  // add patches
  me.insertAtStart(new Patch() { … });        (3)
  me.insertBefore(j, new Patch() { … });      (4)
  …
  // apply patches (simultaneously)
  me.applyPatches(); me.endPass();            (5)
}
```

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Shrike Clients

- Small example: see `com.ibm.wala.shrike.bench.Bench`
- Dila (`com.ibm.wala.dila` in incubator)
  - Dynamic call graph construction (`CallGraphInstrumentation`)
  - Utilities for runtime instrumentation
    - Instrumenting class loader
    - Mechanisms for controlling what gets instrumented
  - Work continues on better WALA integration / docs

Java Annotation Support

- **Supported features**
  - Reading .class file attributes
  - Parsing some annotation info from attributes
    - E.g., generics (`com.ibm.wala.types.generics`)
  - Manipulating JVM class attributes directly
    - See `ClassWriter.addClassAttribute()`
- **Missing features**
  - Higher-level APIs for modifying known annotations
  - Automatic fixing of StackMapTable attribute after instrumentation
    - Speeds bytecode verification in Java 6

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Eclipse Support

- WALA projects are Eclipse plug-ins
  - Easy to invoke from other plug-in
- Various utilities in `com.ibm.wala.ide` project
  - `EclipseProjectPath`: creates `AnalysisScope` for Eclipse project
  - `JdtUtil`: find all Java projects, code within projects, etc.
- JDT CAst frontend for Java source analysis
- Prototype utils in `com.ibm.wala.eclipse` project
  - E.g., display call graph for selected project

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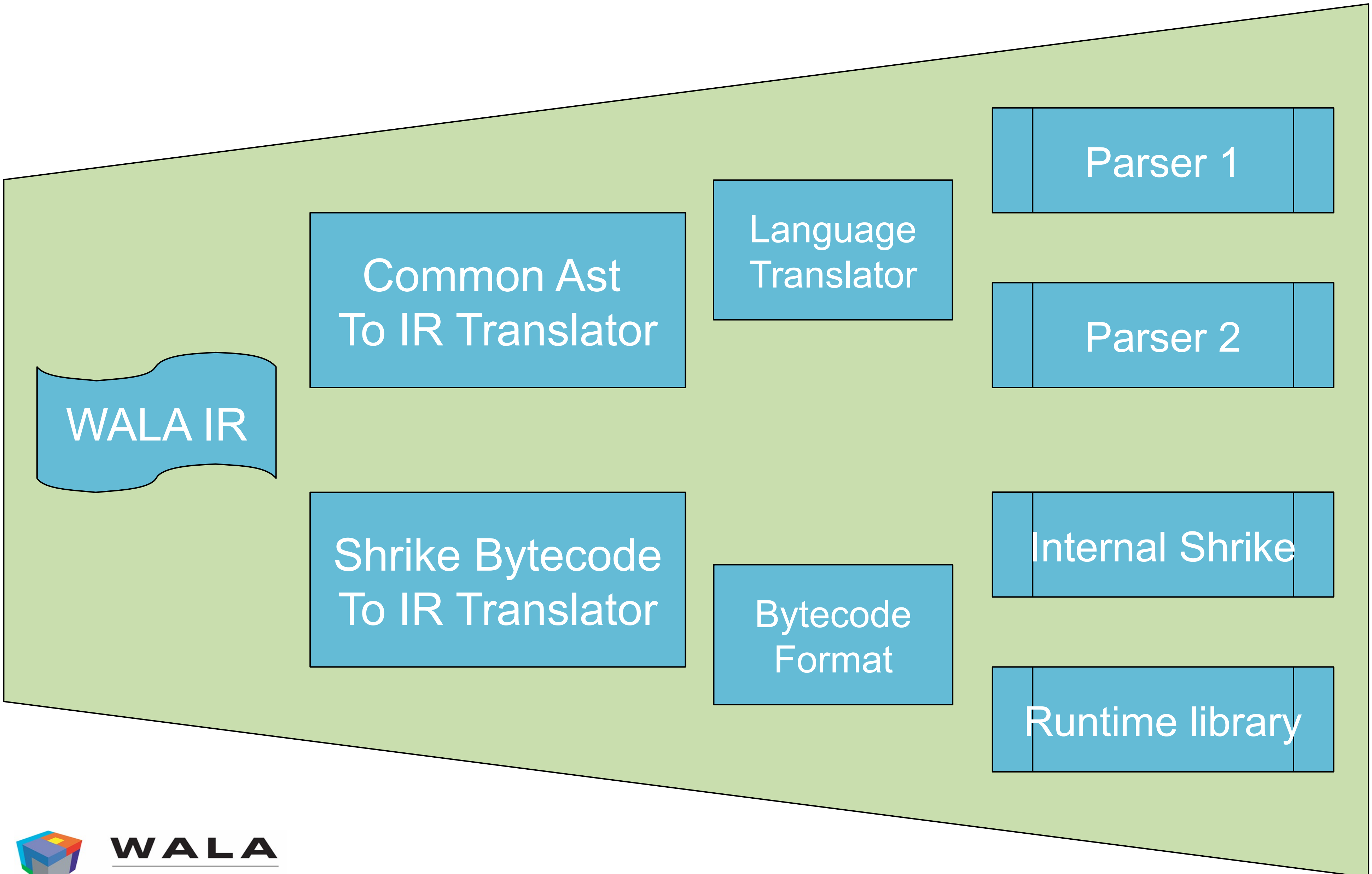
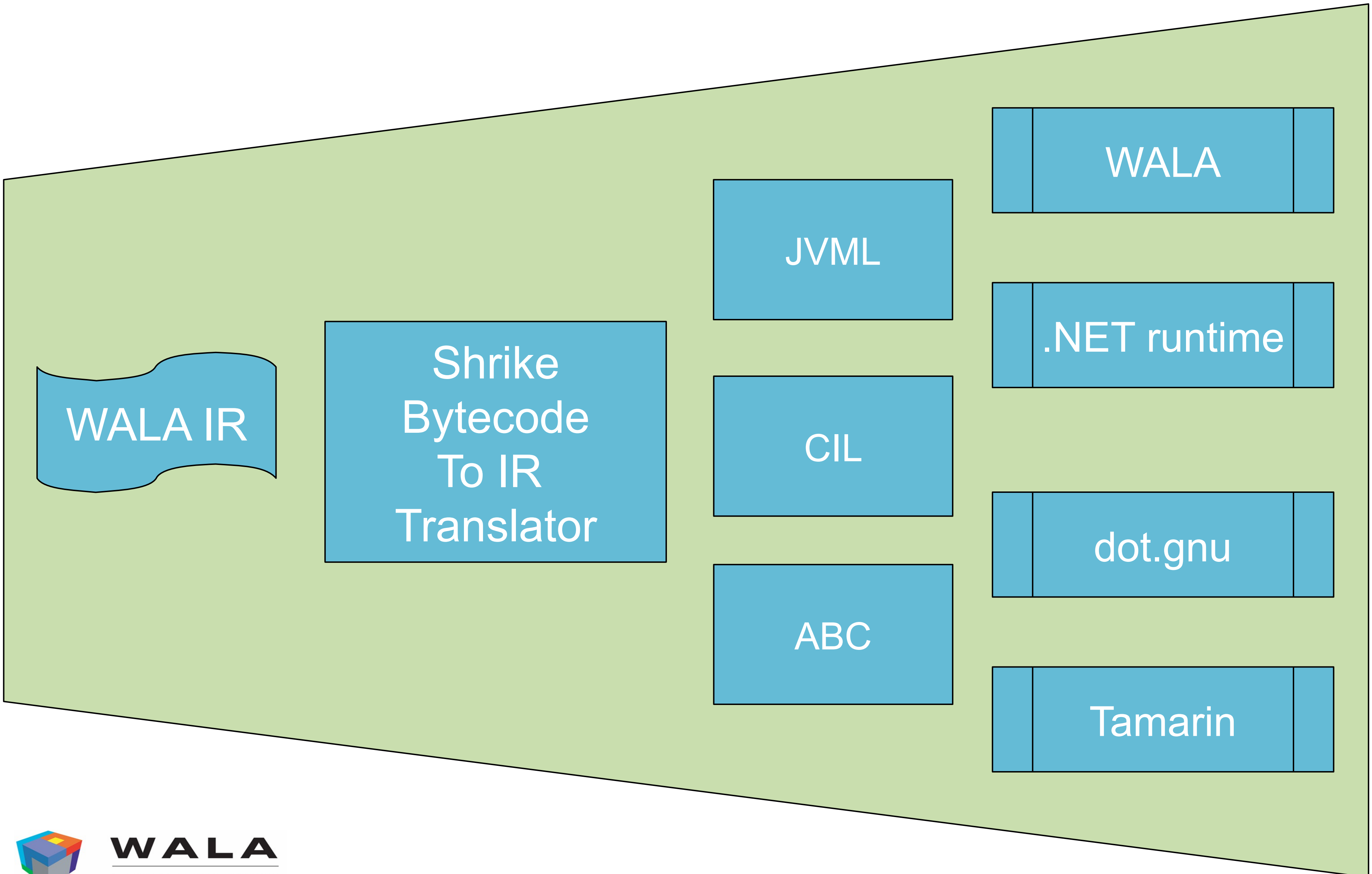
FRONT ENDS / CAST

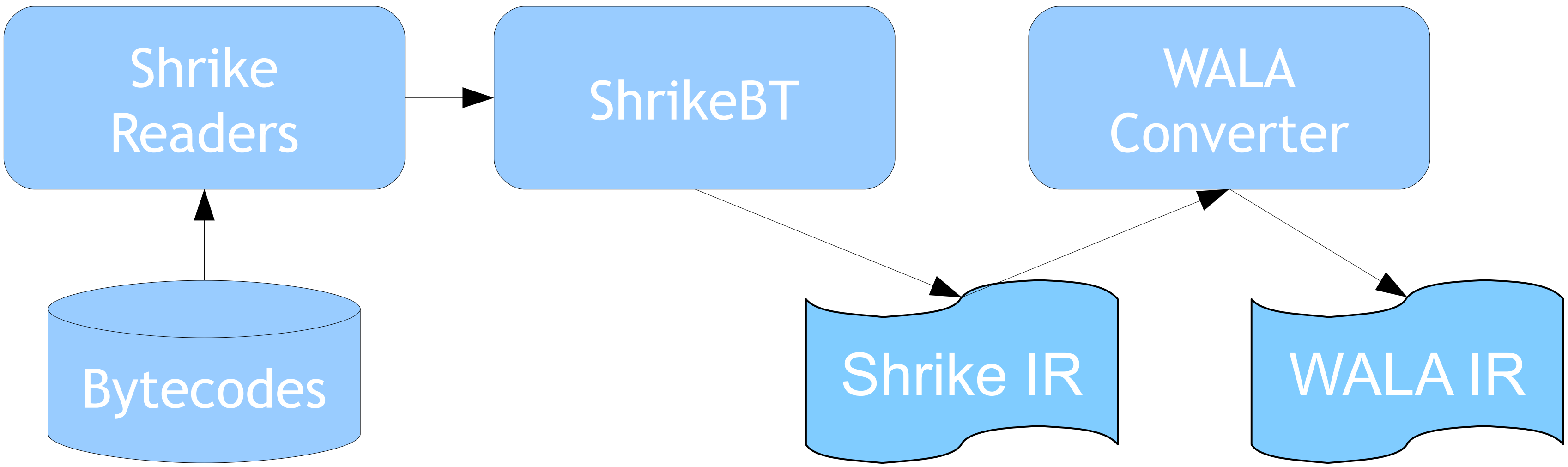
WALA Front End



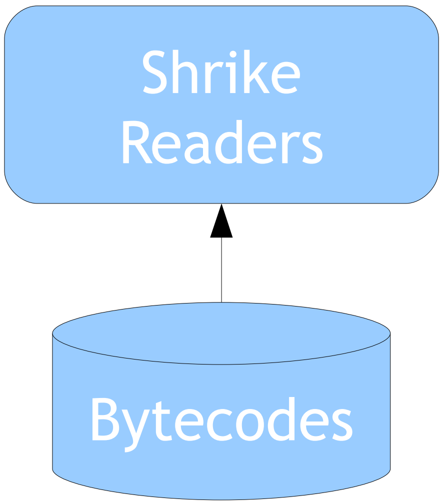
WALA Bytecode Front End



Shrike IR Construction



Shrike Readers



ShrikeCT

- JVML (java bytecode)

GNU dot.gnu

- CIL
- (internal IBM only)

WIN32

- CIL
- (IBM; Windows only)

Mozilla Tamarin

- ABC (ActionScript)
- (under development)

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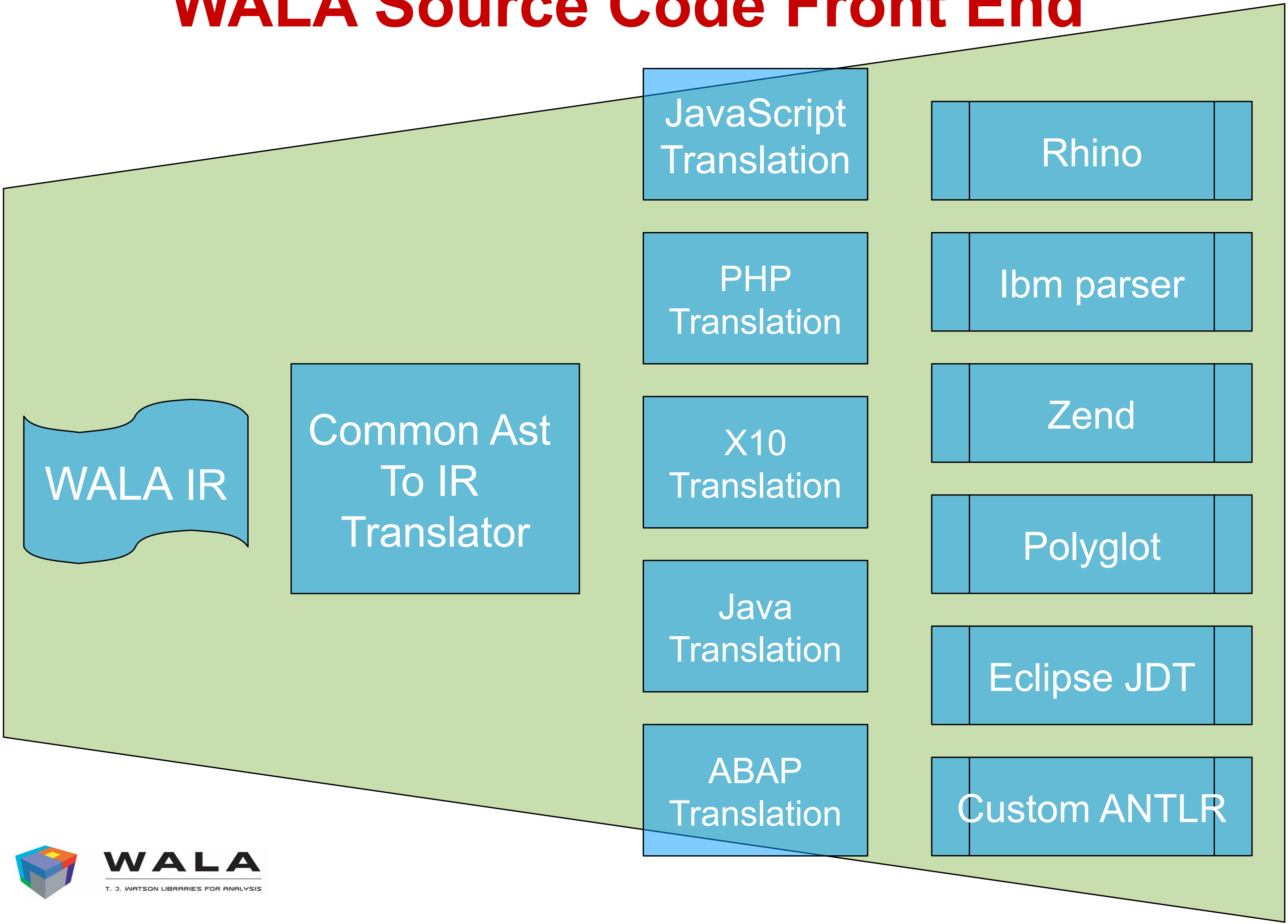
WALA Source Code Front End



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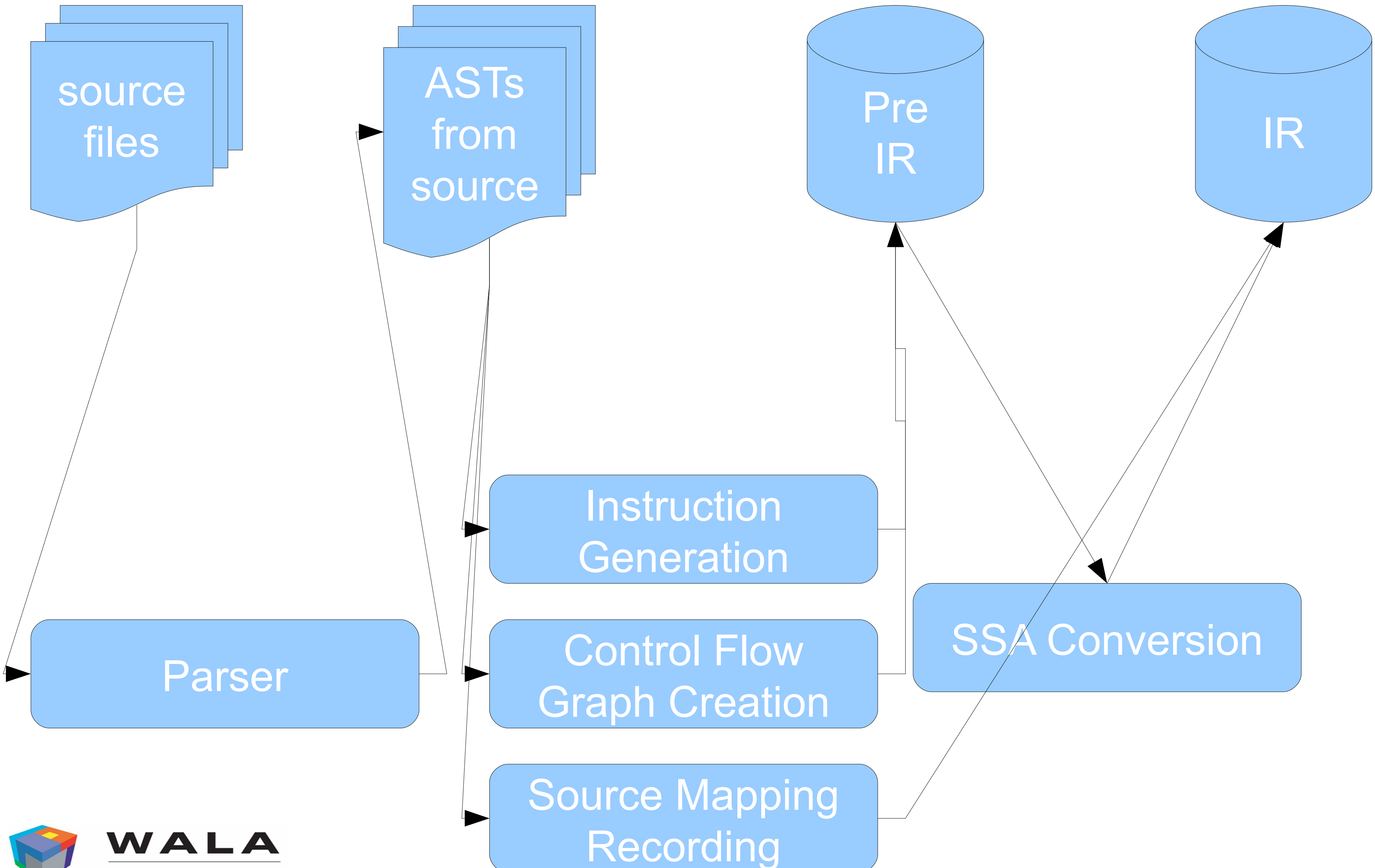
CAst IR Generation



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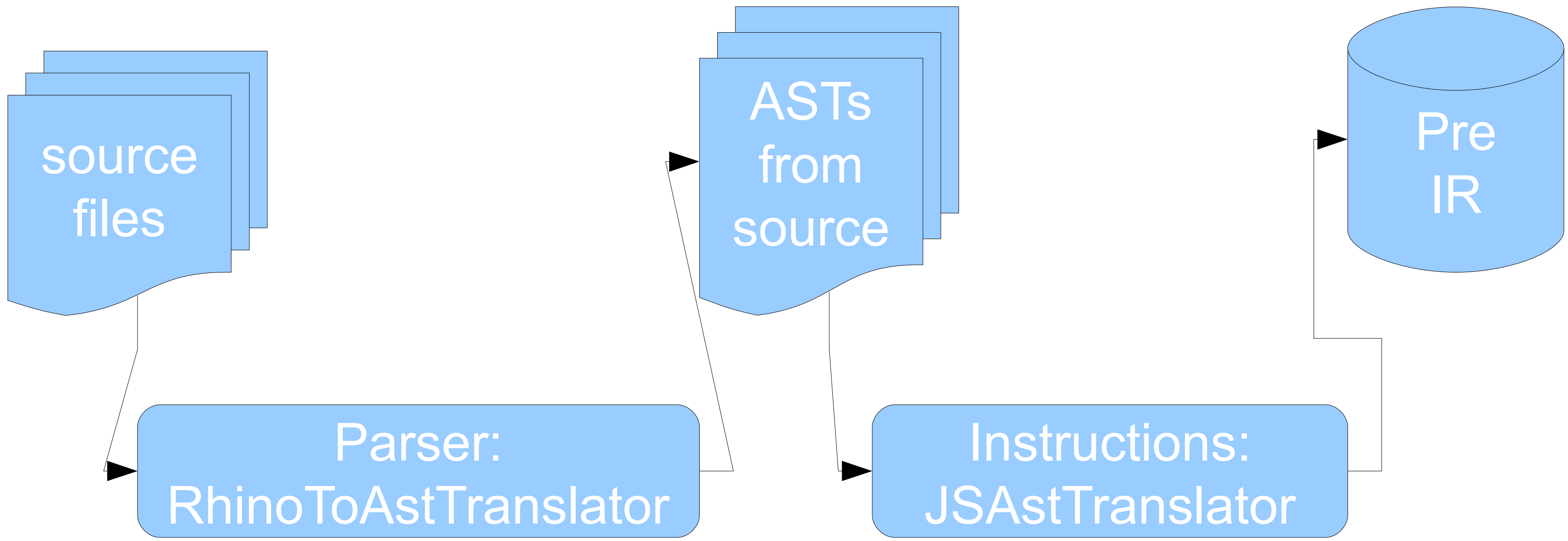
JavaScript Instruction Generation



- **Translate Rhino structures to WALA Common AST (CAst)**
  - **Combination of generic and JavaScript AST nodes**
  - **Only piece of code that understands Rhino**
- **Translate CAst AST to WALA Pre IR form**
  - **Shared by another internal JavaScript translator**
  - **Extends generic translation machinery**

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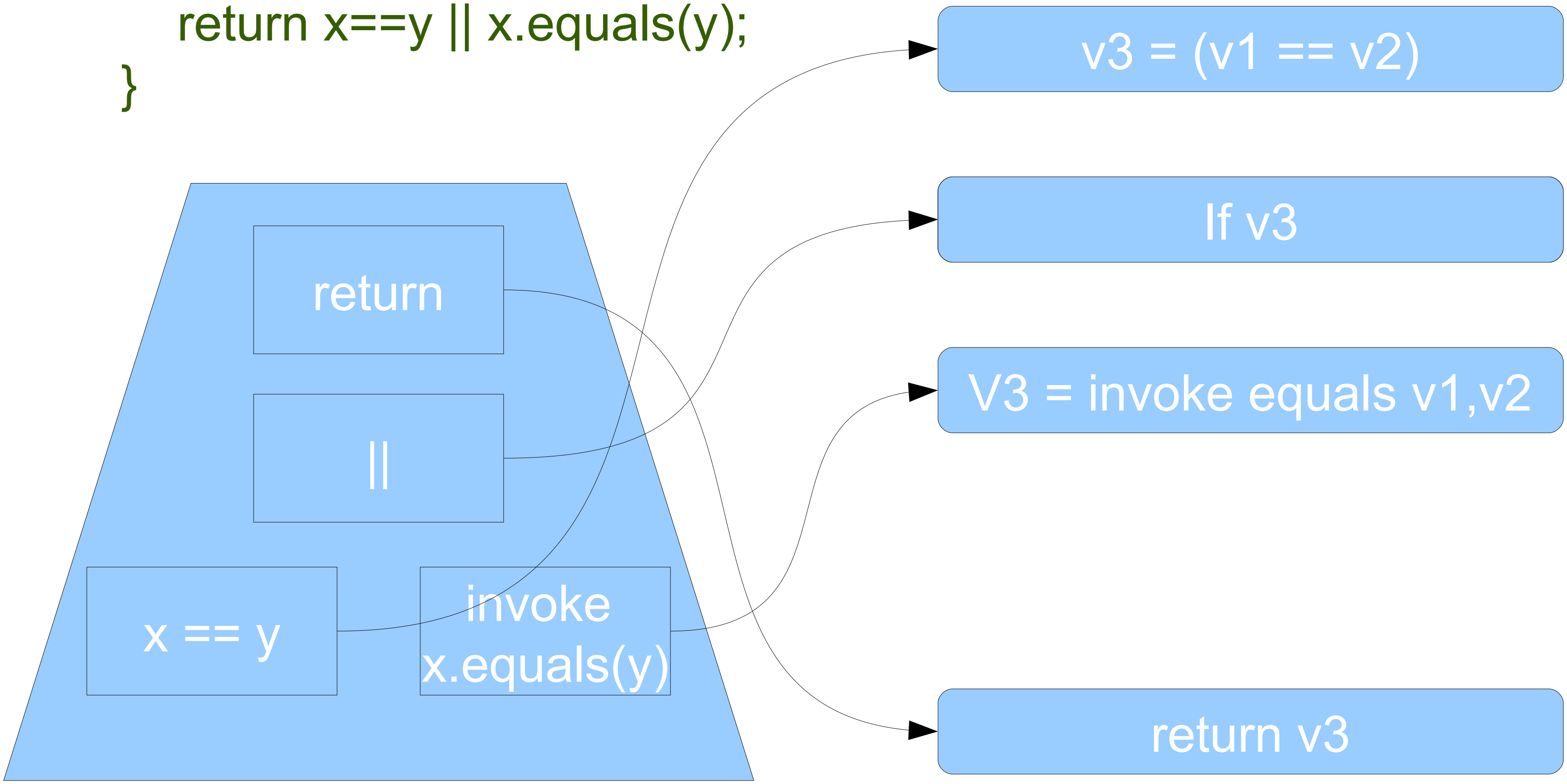
Instruction Generation

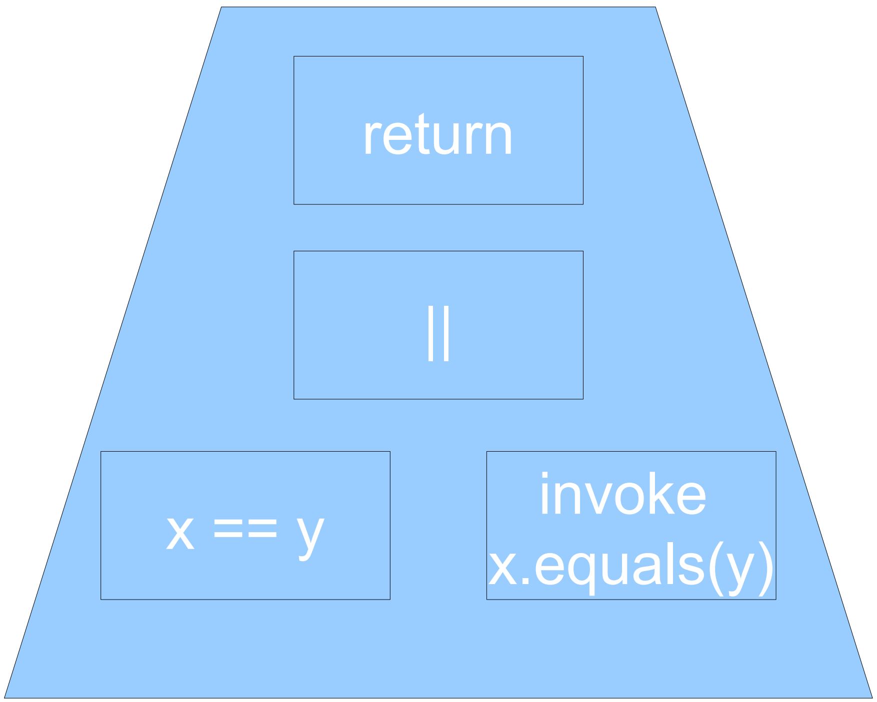
```
foo(x, y) {
    return x==y || x.equals(y);
}
```



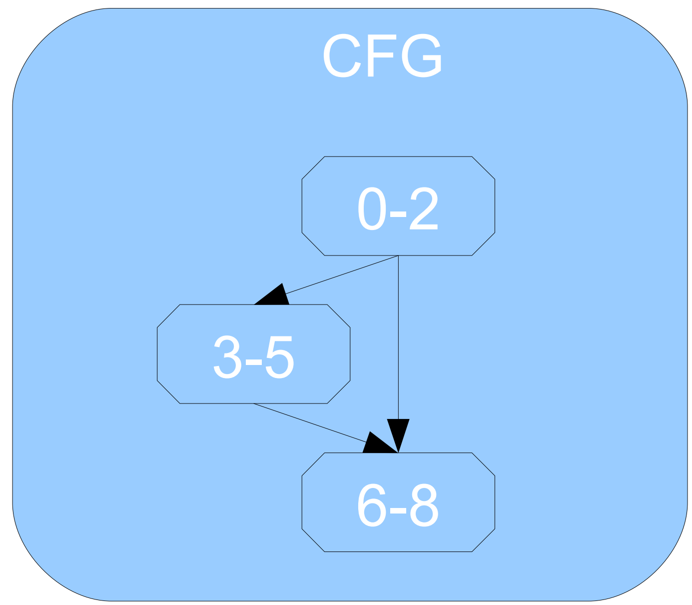
AstTranslator implements recursive AST tree walk

Control Flow Graph Creation

```
foo(x, y) {
    return x==y || x.equals(y);
}
```




```
getBlock(x : ||) {
  b1= getBlock(x.left);
  b2 = getBlock(x.right);
  b3 = new Block()
  b1.successor = b3;
  b3.add([b1.v == true])
  b3.false = b2;
}
```



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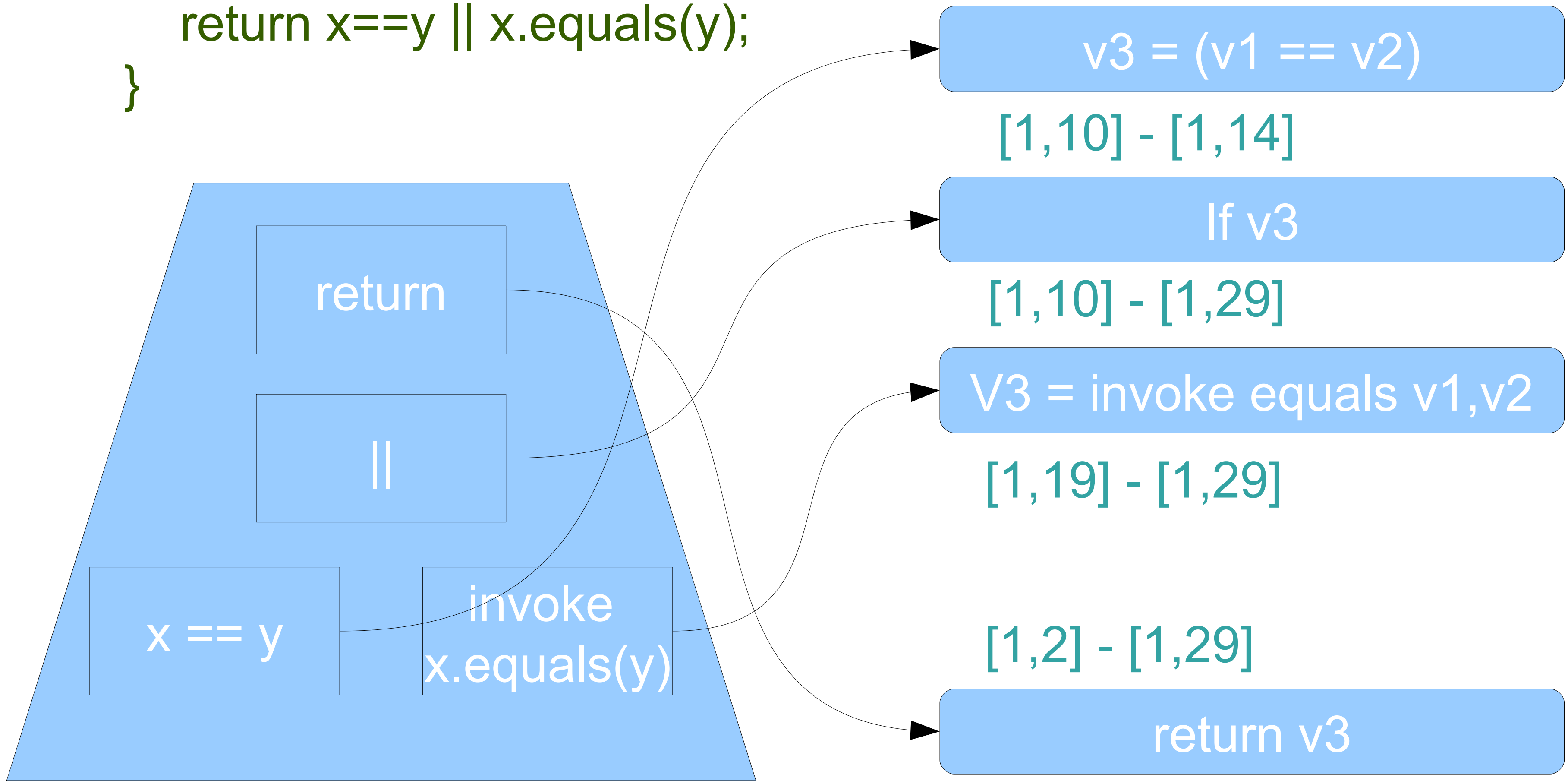
AstTranslator builds CFG recursively over the AST

Source Position Mapping

```
foo(x, y) {
    return x==y || x.equals(y);
}
```



AstTranslator copies source positions from AST

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SSA Conversion

```
v3 = (v1 == v2)

If v3

v3 = invoke equals v1,v2

return v3
```

```
v3 = (v1 == v2)

If v3

v4 = invoke equals

v5 = ϕ(v3,v4)

return v5
```

WALA does copy propagation in SSA conversion

WALA implements fully-pruned SSA Conversion

- i.e. phis only inserted for live values

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