AutoHacking with Phoenix Enabled Data Flow Analysis

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Topics

- Phoenix
  - Architecture
  - Fundamentals

- Program Analysis
  - Call Flow
  - Control Flow
  - Data Flow

- Applied Program Analysis
  - API Path Validation
  - Integer Overflow Detection
  - Syntax Model Inference

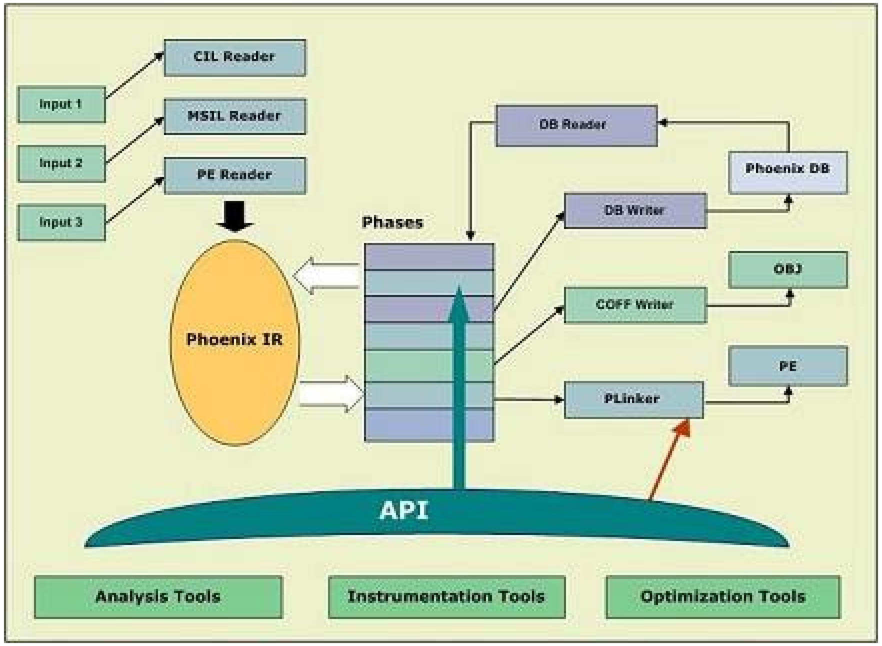
Introducing Phoenix

- Framework for building compilers and program analysis tools
- Collabo Microsoft
  Researc mmon
  Language Runtime groups at Microsoft
- Foundation for the next generation of Microsoft development tools

Phoenix Architecture

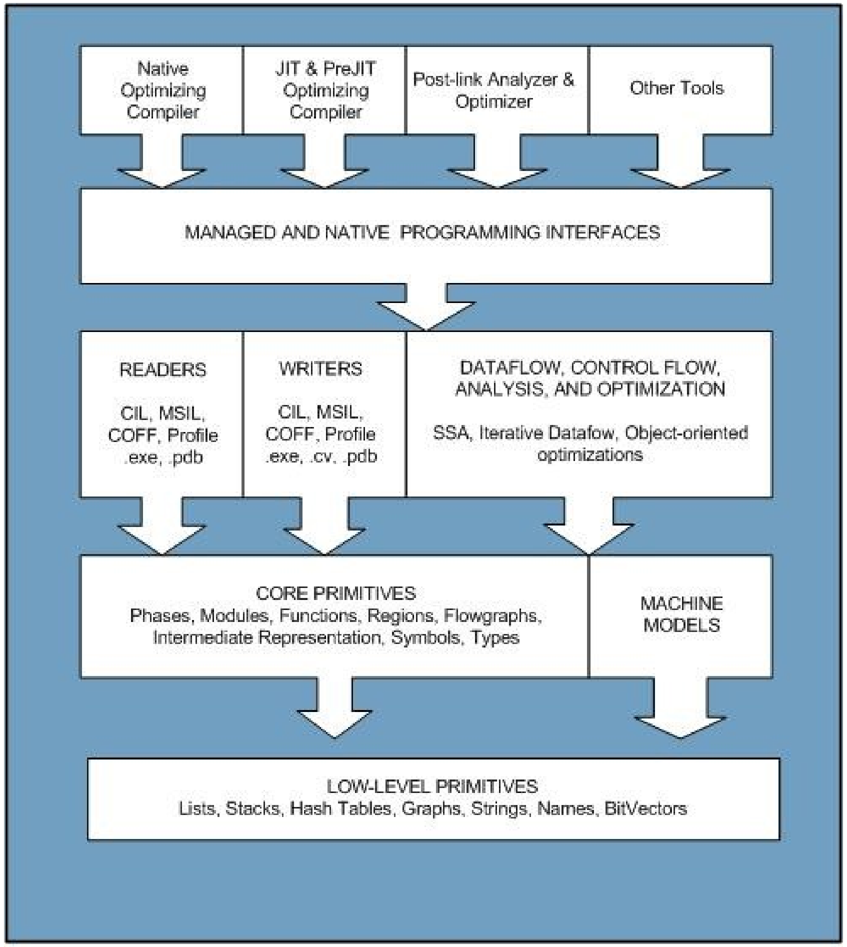
- Inputs are converted to an intermediate representation (IR)

- Phoenix API allows compiler plug-ins or standalone tools to add or hook phases of IR creation

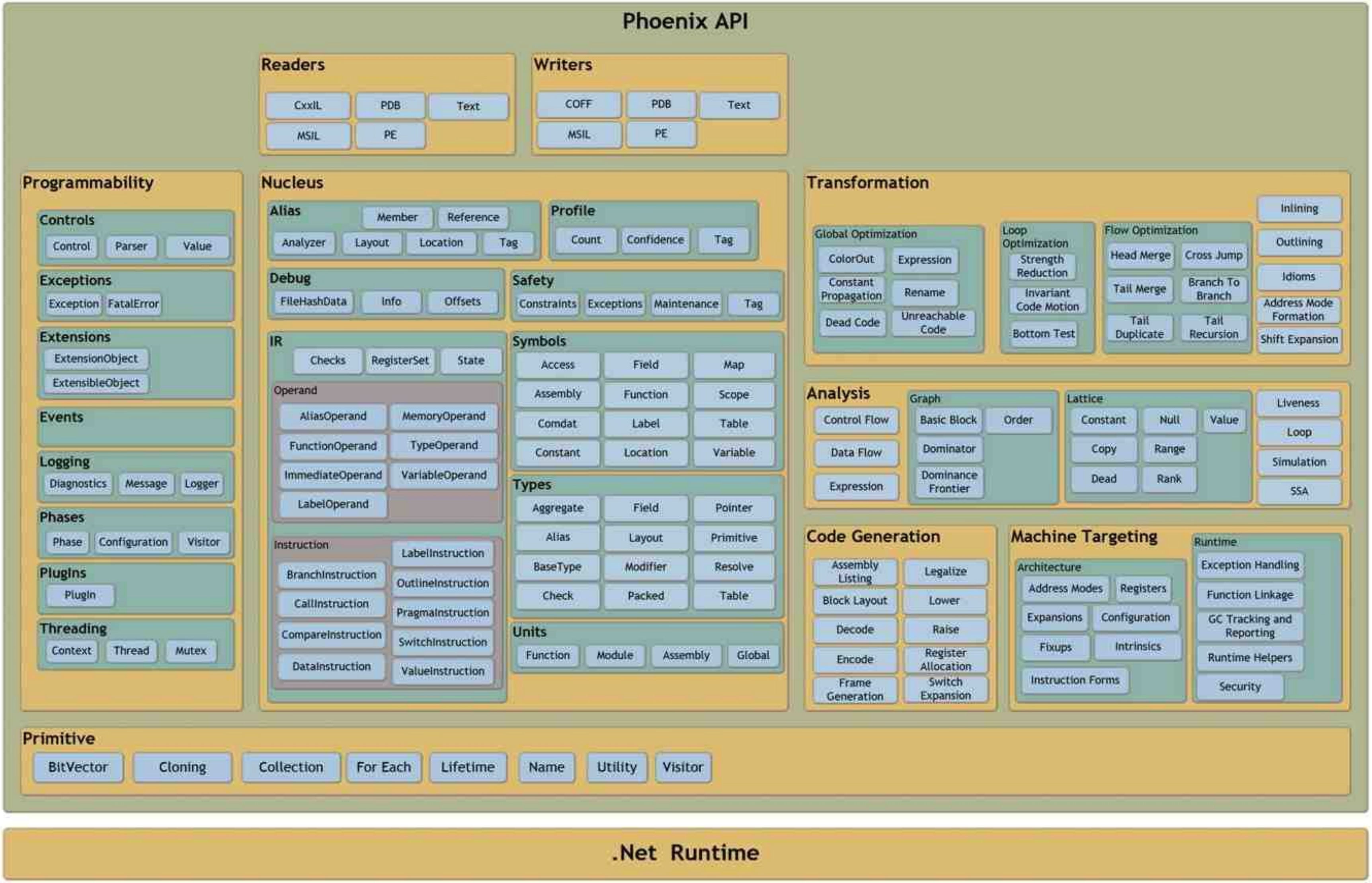


Phoenix Architecture

- Phases process IR to provide abstractions such as call graphs, flow graphs, region graphs, single static assignment (SSA) annotations



Phoenix Architecture



Phoenix API

- **Readers**
  - CxxIL
  - PDB
  - Text
  - MSIL
  - PE
- **Writers**
  - COFF
  - PDB
  - Text
  - MSIL
  - PE
- **Programmability**
  - Controls
    - Control
    - Parser
    - Value
  - Exceptions
    - Exception
    - FatalError
  - Extensions
    - ExtensionObject
    - ExtensibleObject
  - Events
  - Logging
    - Diagnostics
    - Message
    - Logger
  - Phases
    - Phase
    - Configuration
    - Visitor
  - Plugins
    - Plugin
  - Threading
    - Context
    - Thread
    - Mutex
- **Nucleus**
  - Alias
    - Member
    - Reference
    - Analyzer
    - Layout
    - Location
    - Tag
  - Profile
    - Count
    - Confidence
    - Tag
  - Debug
    - FileHashData
    - Info
    - Offsets
  - Safety
    - Constraints
    - Exceptions
    - Maintenance
    - Tag
  - IR
    - Checks
    - RegisterSet
    - State
    - Operand
      - AliasOperand
      - MemoryOperand
      - FunctionOperand
      - TypeOperand
      - ImmediateOperand
      - VariableOperand
      - LabelOperand
    - Instruction
      - LabelInstruction
      - BranchInstruction
      - OutlineInstruction
      - CallInstruction
      - PragmaInstruction
      - CompareInstruction
      - SwitchInstruction
      - DataInstruction
      - ValueInstruction
  - Symbols
    - Access
    - Field
    - Map
    - Assembly
    - Function
    - Scope
    - Comdat
    - Label
    - Table
    - Constant
    - Location
    - Variable
  - Types
    - Aggregate
    - Field
    - Pointer
    - Alias
    - Layout
    - Primitive
    - BaseType
    - Modifier
    - Resolve
    - Check
    - Packed
    - Table
  - Units
    - Function
    - Module
    - Assembly
    - Global
- **Transformation**
  - Global Optimization
    - ColorOut
    - Expression
    - Constant Propagation
    - Rename
    - Dead Code
    - Unreachable Code
  - Loop Optimization
    - Strength Reduction
    - Invariant Code Motion
    - Bottom Test
  - Flow Optimization
    - Head Merge
    - Cross Jump
    - Tail Merge
    - Branch To Branch
    - Tail Duplicate
    - Tail Recursion
  - Inlining
  - Outlining
  - Idioms
  - Address Mode Formation
  - Shift Expansion
- **Analysis**
  - Control Flow
  - Data Flow
  - Expression
  - Graph
    - Basic Block
    - Order
    - Dominator
    - Dominance Frontier
  - Lattice
    - Constant
    - Null
    - Value
    - Copy
    - Range
    - Dead
    - Rank
  - Liveness
  - Loop
  - Simulation
  - SSA
- **Code Generation**
  - Assembly Listing
  - Legalize
  - Block Layout
  - Lower
  - Decode
  - Raise
  - Encode
  - Register Allocation
  - Frame Generation
  - Switch Expansion
- **Machine Targeting**
  - Architecture
    - Address Modes
    - Registers
    - Expansions
    - Configuration
    - Fixups
    - Intrinsics
    - Instruction Forms
  - Runtime
    - Exception Handling
    - Function Linkage
    - GC Tracking and Reporting
    - Runtime Helpers
    - Security
- **Primitive**
  - BitVector
  - Cloning
  - Collection
  - For Each
  - Lifetime
  - Name
  - Utility
  - Visitor

.Net Runtime

Phoenix Applications

- Compiler development
  - Optimization
  - Retargeting

- Binary Instrumentation
  - Profiling/Code coverage
  - Binary protection/obfuscation

- Program Analysis
  - Model inference
  - Vulnerability detection

Using Phoenix

- Load targets manually or via plug-ins
- Use phase lists or raise binaries

```
PEModuleUnit module = null;

module = PEModuleUnit.Open(path);
module.LoadPdb();
module.LoadGlobalSymbols();

Phx.Symbols.Table table = module.SymbolTable;
Phx.Symbols.LocalIdMap localMap = table.LocalIdMap;
Phx.Collections.IdToSymbolMap symbolMap = localMap.InternalMap;
Phx.Collections.IdToSymbolMap.Iterator iterator =
     new Phx.Collections.IdToSymbolMap.Iterator(symbolMap);

while (iterator.MoveNext())
{
  if (iterator.CurrentValue.IsFunctionSymbol)
  {
    FunctionSymbol function =  iterator.CurrentValue.AsFunctionSymbol;
```

Using Phoenix

- Load targets manually or via plug-ins
- Use phase lists or raise binaries

```
public class PlugIn : Phx.PlugIn {

public override void BuildPhases
(Phx.Phases.PhaseConfiguration config)
{
  Phx.Phases.Phase funcNamesPhase;
  funcNamesPhase = Phase.New(config);

  Phx.Phases.Phase encodingPhase =

config.PhaseList.FindByName("Encoding");


encodingPhase.InsertBefore(funcNamesPhase)
;
}

public override System.String NameString
{
   get { return "FuncNames"; }
}
```

```
public class Phase : Phx.Phases.Phase
{

public static Phx.Phases.Phase
New (Phx.Phases.PhaseConfiguration
config)
{
  Phase phase = new Phase();
  phase.Initialize(config,
"FuncNames");
  return phase;
}

protected override void
Execute (Phx.Unit unit)
{
  if (!unit.IsFunctionUnit) return;

   Phx.FunctionUnit function =
     unit.AsFunctionUnit;
```

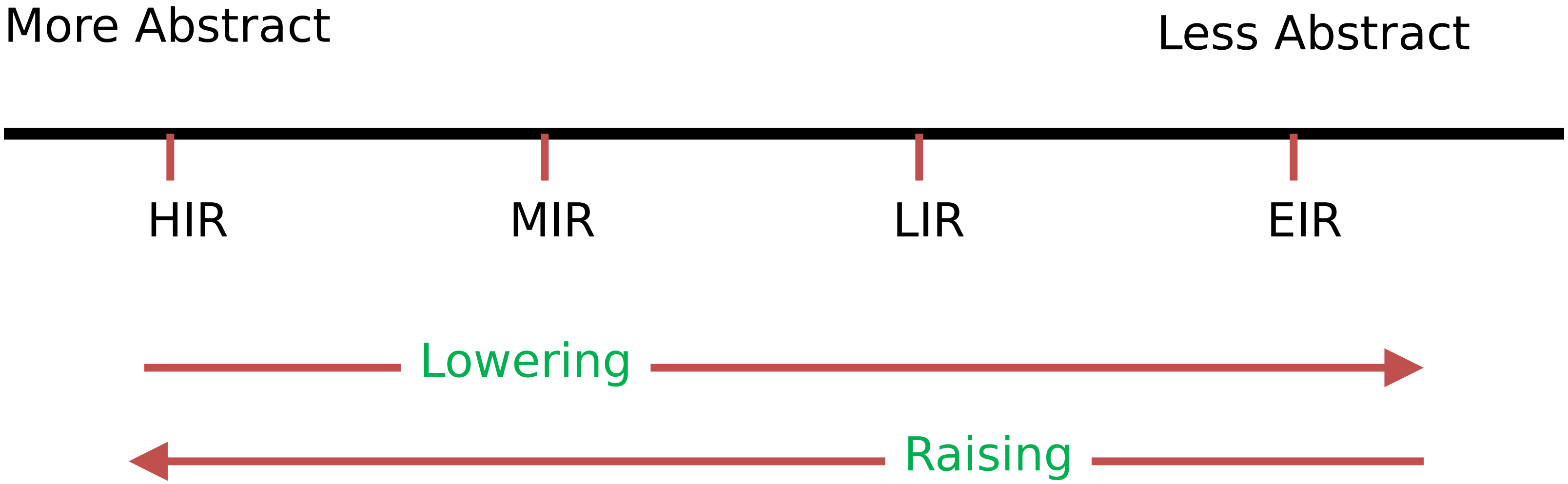
Using Phoenix

- Units
  - Programs, Assemblies, Modules, Functions
- Types
  - Primitives, Symbolic
- Symbols
  - Static, Dynamic

- Intermediate Representation
  - Primary abstraction of program semantics
  - Composed of Instructions and Operands
  - Three distinct levels of abstraction

Phoenix Intermediate Representation

- High-level IR (HIR)
  - Architecture Independent
  - Abstract instructions represent runtime indirection
  - Operands refer to logical resources



More Abstract

Less Abstract

HIR

MIR

LIR

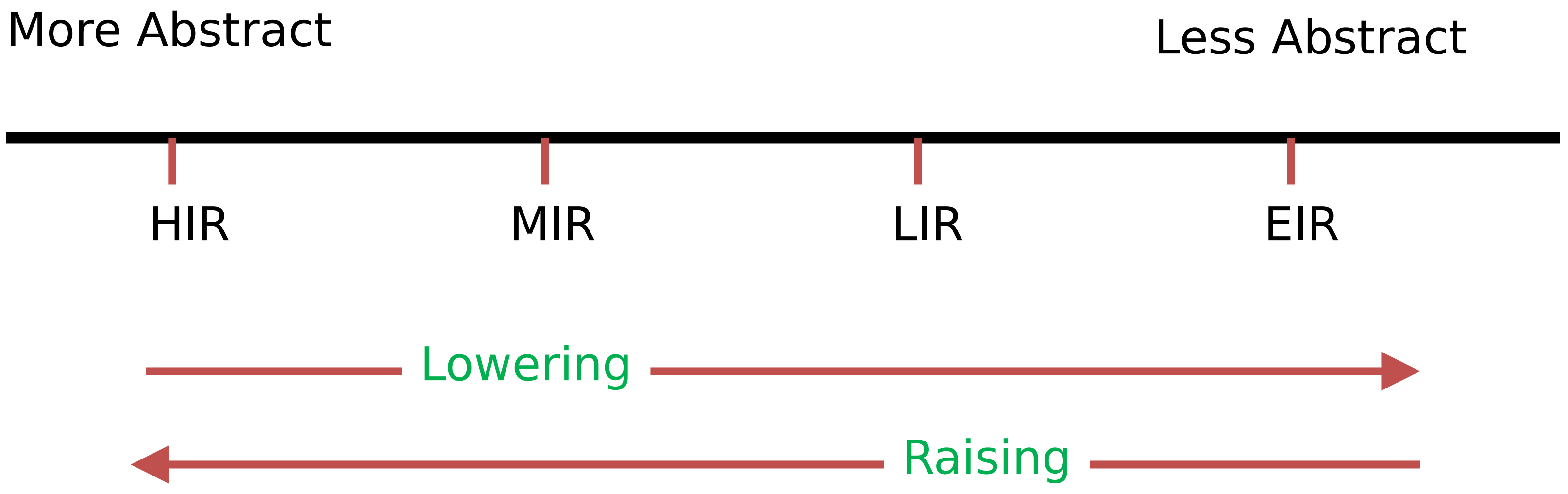
EIR

Lowering

Raising

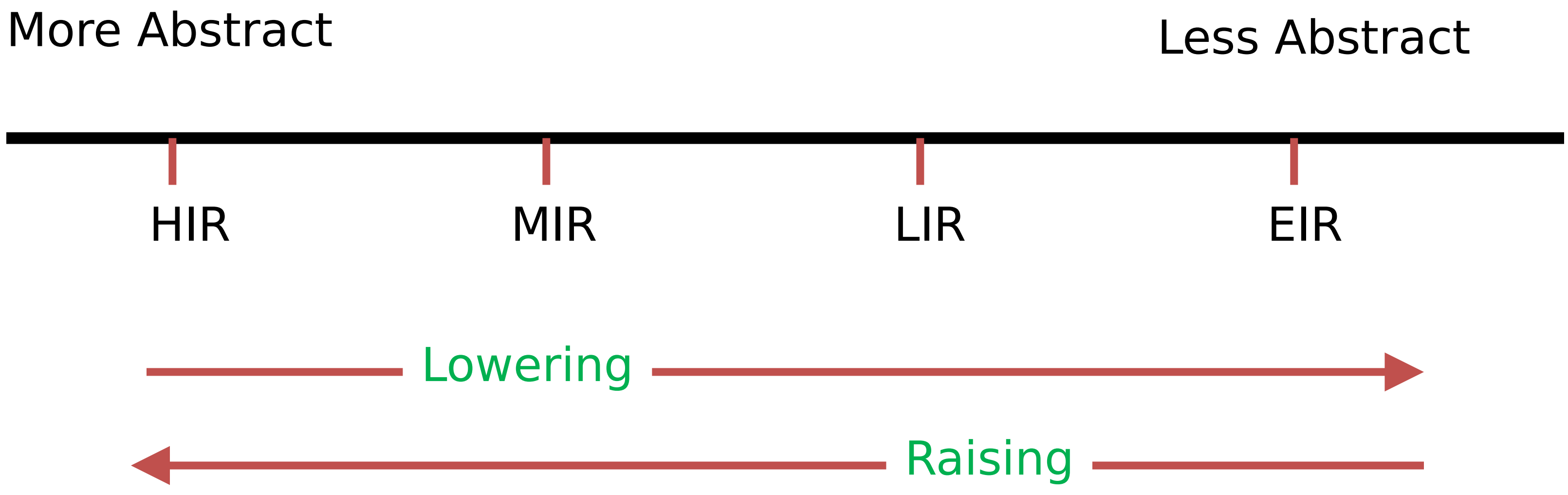
Phoenix Intermediate Representation

- Mid-level IR (MIR)
  - Architecture Independent
  - Runtime logic explicitly defined
  - Operands still refer to logical resources



Phoenix Intermediate Representation

- Low-level IR (LIR)
  - Architecture dependent
  - Control flow explicit
  - Operands refer to logical or physical resources


More Abstract

Less Abstract

HIR

MIR

LIR

EIR

Lowering

Raising

Phoenix Instructions

- Code or Data object
- Source and Destination Operands
- Annotation Operands

- Types
  - Label
  - Value
  - Compare
  - Branch
  - Call

High-level IR

```
$L1: (references=0)

   {*StaticTag}, {*NotAliasedTag} = START _main(T)

_main: (references=1)

   _argc, _argv   = ENTERFUNCTION

   t273           = COMPARE(GT) _argc, 1

                  CONDITIONALBRANCH(True) t273,
$L7, $L6
$L7: (references=1)

   _message       = ASSIGN &$SG3745

                    GOTO $L8
```

Low-level IR

```
   tv144-             = mov 4112(0x00001010)
   {ESP}              = call _chkstk, {ESP}

   offset             = mov 8
   tv144-, {ESP}      = call CreateHeader, {ESP}

   header             = mov tv144-
   $Stack+32928, {ESP} = push 8
   $Stack+32960, {ESP} = push header
   tv144-             = lea &buf*
```

Phoenix Operands

- Instruction arguments
- Temporary Variables
- Alias Tags
- Alias Operands

- Types
  - Memory
  - Constants
  - Variables
  - Functions
  - Labels
  - Alias Sets

High-level IR

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   tv144-              = lea &buf*
```

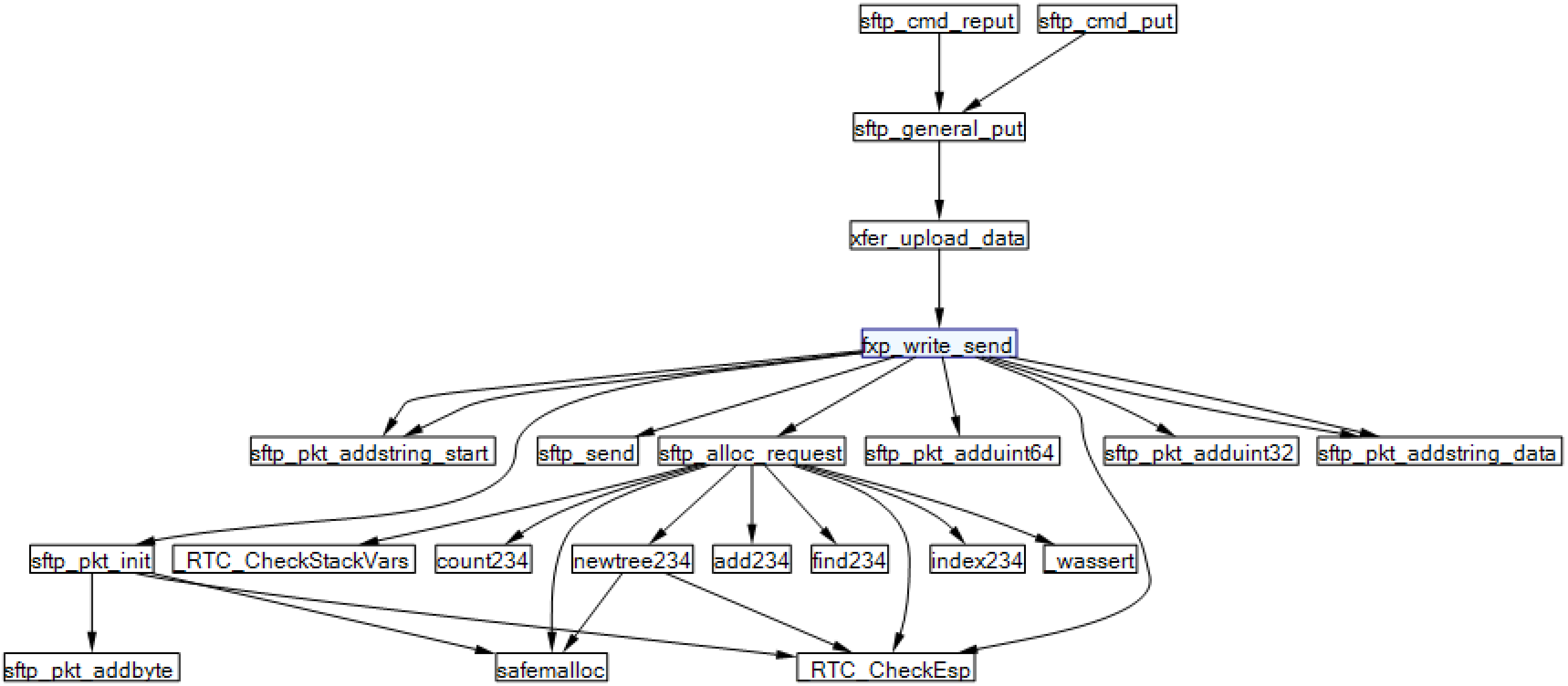
Phoenix Alias Package

- Alias System provides a memory model for static program analysis
- Aliases abstract memory and register use by assigning tags to discrete locations
- Alias Operands added to represent implicit effects of an instruction on memory

```
[ESP], {ESP} = push _message[EBP]
```

Call Graphs

- A Call Graph is a visual representation of call relationships



Call Graphs

- Traditional call graph generation

Collect all call edges

```
foreach(Function in ModuleFunctions)
   foreach(CallInstruction in Instructions)
      AddCallEdge(Function, CallTarget))
```

Find edges for Function

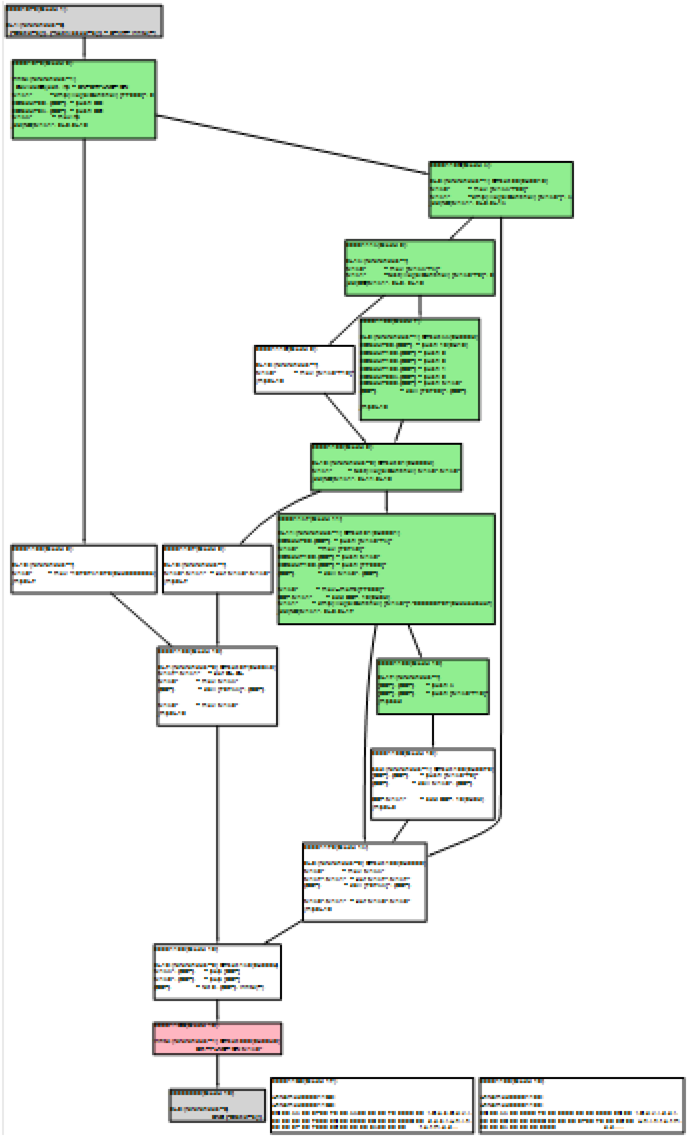
```
foreach(Edge in CallEdges)
   if(Target == Function)
      EdgesTo.Add(Edge)
   if(Source == Function)
      EdgesFrom.Add(Edge)
```

- Phoenix includes a Call Graph Package that provides module or program level function relationships

Control Flow Graphs

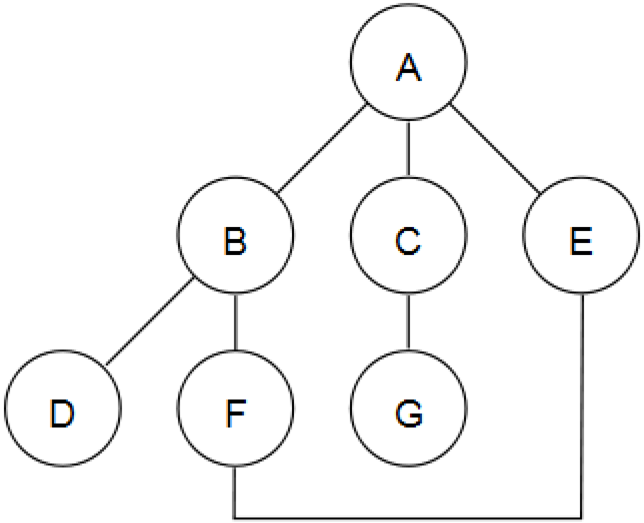
- Control Flow Graph are visual representations of branch relationships between basic blocks

- Phoenix provides a Control Flow Graph package that specifies edge types, node types, node dominance



Graph Traversal

- Depth First Search
  - Visit nodes following edges as deep as possible before returning to the next edge



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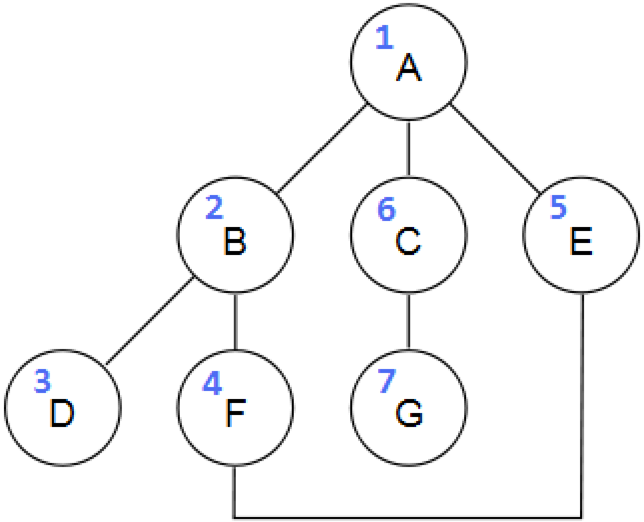

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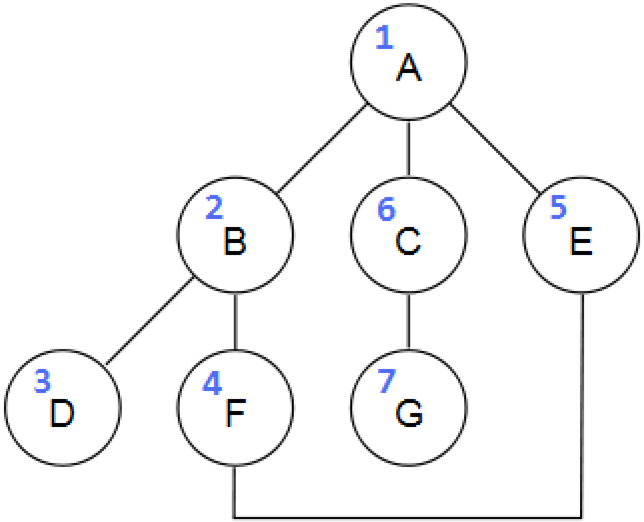

- DFS Outputs
  - Spanning Tree (DAG)
  - Preordered Vertices
  - Postordered Vertices
  - Reverse Postorder Vertices

Reaching Definition Analysis

- A variable assignment $[x := a]^l$ may reach a code location if there is an execution of the program where x was last assigned at l when the code location is reached
- An assignment reaches the entry of a block if it reaches the exit of any of the blocks that precede it

Reaching Definition Analysis

```
x = 5;
y = 1;
while (x > 1)
{
    y = x * y;
    --x;
}
```

Reaching Definition Analysis

```
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y = 1;
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    y = x * y;
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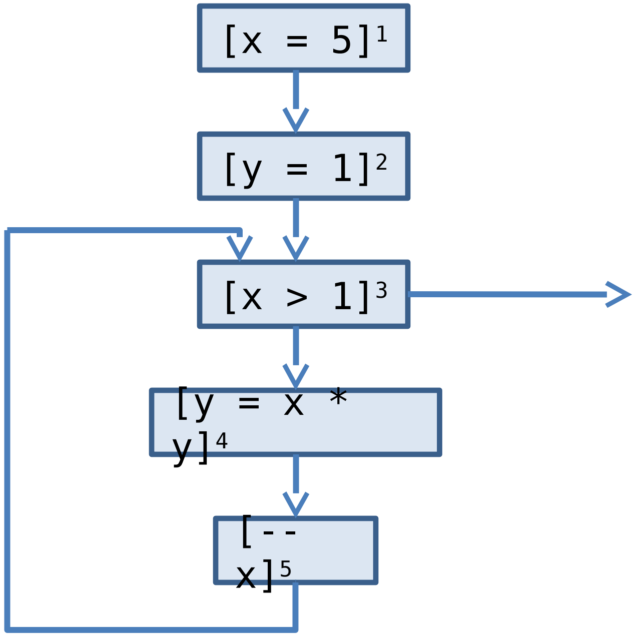
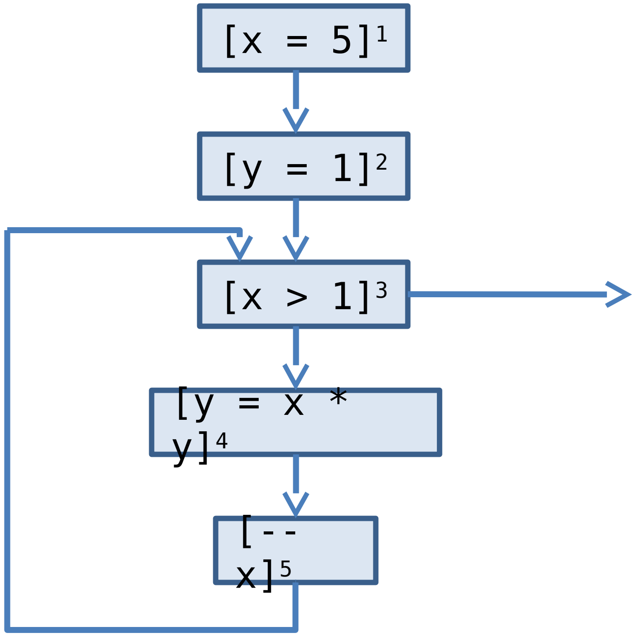


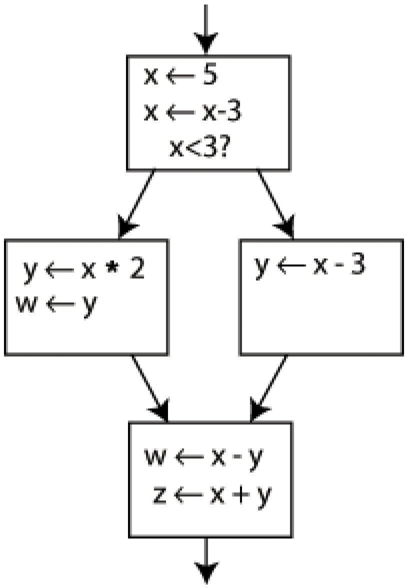
Reaching Definition Analysis

	RD_{entry}	RD_{exit}
1	(x, ?), (y, ?)	(x, 1), (y, ?)
2	(x, 1), (y, ?)	(x, 1), (y, 2)
3	(x, 1), (x, 5), (y, 2)	(x, 1), (x, 5), (y, 2)
4	(x, 1), (x, 5) (y, 2), (y, 4)	(x, 1), (x, 5) (y, 4)
5	(x, 1), (x, 5), (y, 4)	(x, 5), (y, 4)



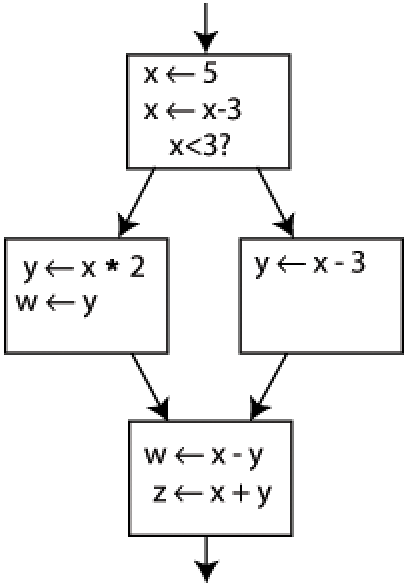
Single Static Assignment

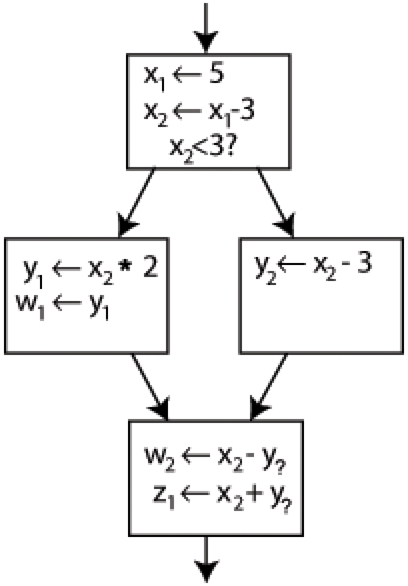
- Intermediate form used by several compilers in which every variable is assigned only once



Single Static Assignment

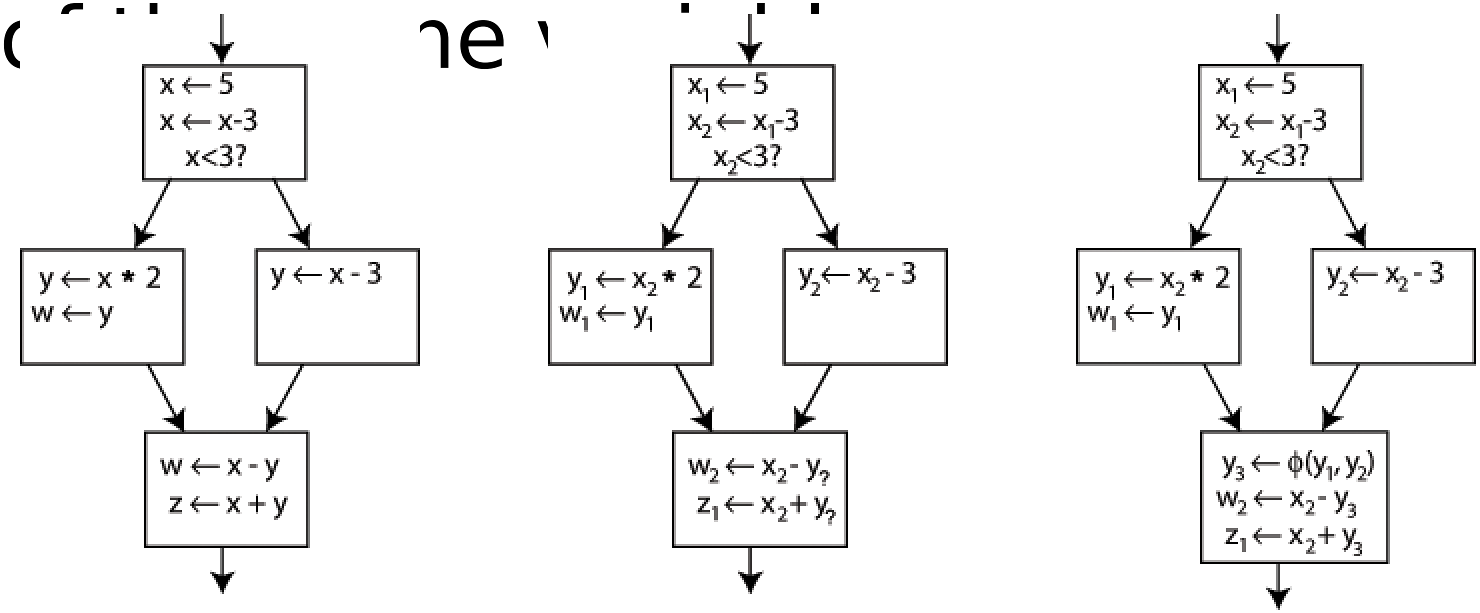
- Use-definition relationships explicit
  - Each use reached by only one definition
  - Each definition dominates all uses





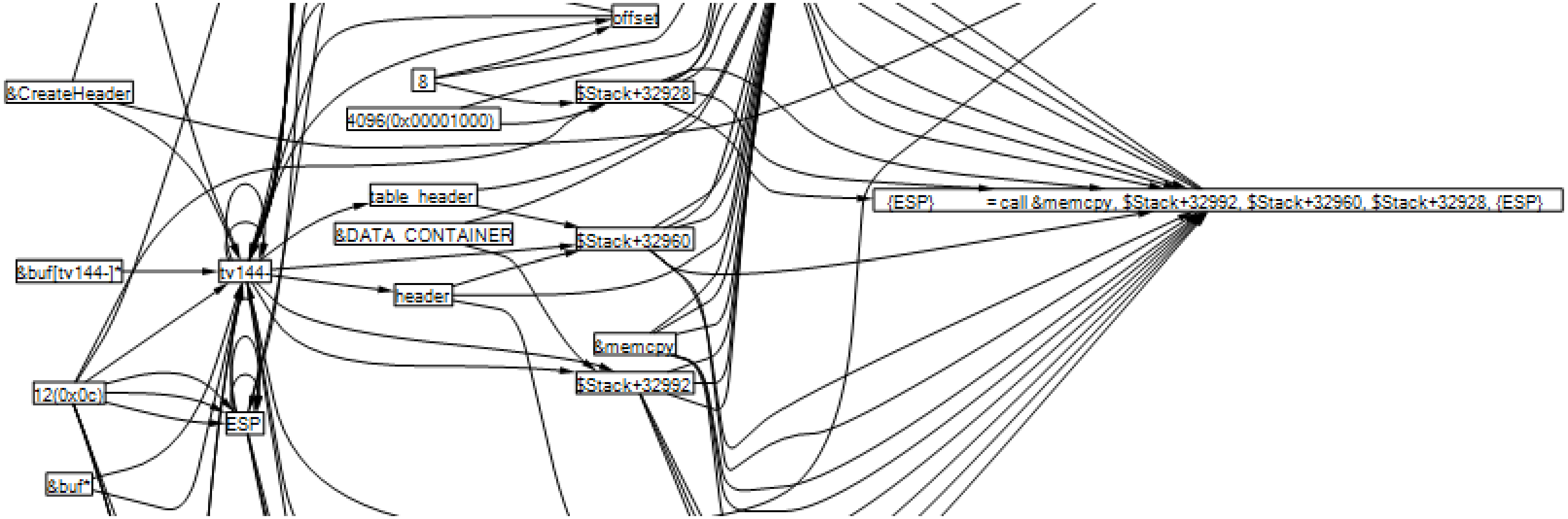
Single Static Assignment

- Special Φ (Phi) instructions are added to the beginning of blocks to represent joins of different versions c ne v



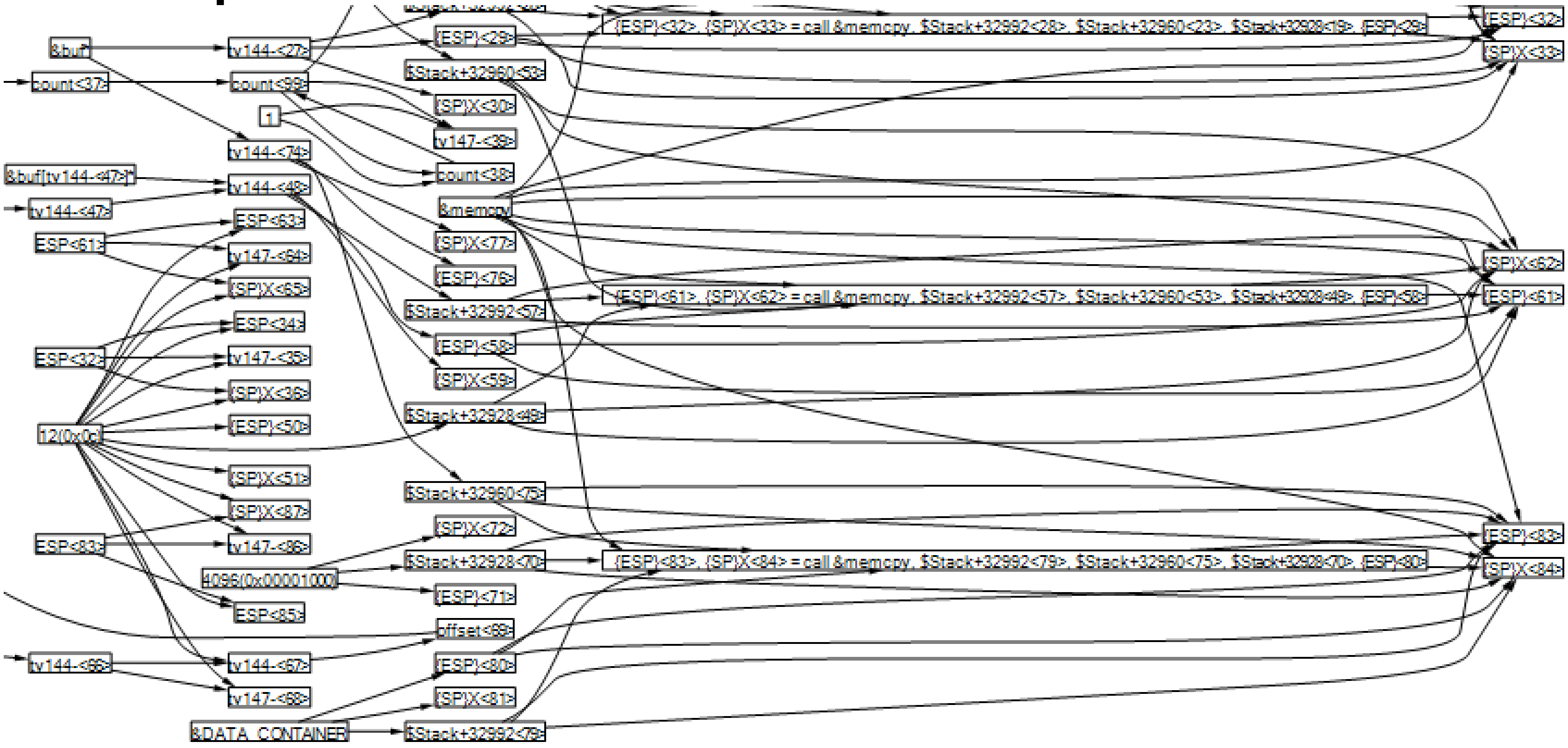
Data Flow Graphs

- Reaching definitions allow the construction of a context-free data flow graph



Data Flow Graphs

- Converting to SSA form allows the simple construction of a contextual



Applied Data Flow Analysis

- API Path Validation
  - Determine whether there is a code path from data input function to a function using the data that does not flow through a sanitizing function

  - Method
    - Create an array of bit vectors to hold each path to each function
    - Propagate inherited bit vectors by performing a union on the two bit vectors

  - Real world use – SQL Injection prevention

Applied Data Flow Analysis

- Syntax Model Inference
  - Determine the type layout of every abstract structure that reaches a specified function call
  - Method
    - Calculate call graph for target function
    - Gather Reaching Definition data for all functions in graph
    - Record type for each definition in each function
    - Walk unique call graph paths backwards collecting type flow information
  - Real world use – generate fuzzer definitions

Applied Data Flow Analysis

- Integer Overflow Detection
  - Given a call to an allocation function, determine whether the input size could have wrapped
  - Method
    - Trace data input to memory allocation functions backward
    - Determine if the value is generated in with potentially user controlled data
  - Real world use – detect bugs!

Final Thoughts

- Phoenix is amazingly powerful and extensible. It will change how academic compiler research is done on the Windows platform
- The security industry has a lot to learn from the academic archives of the last 30 years. Read Dawson Engler, David Wagner, Cousot
- Improved programming processes and advances in static analysis is and will continue to improve software security

Get Involved!

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