Implement Your Own Dynamic Binary Analysis Using the Valgrind Framework

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Outline

1. Introduction
   - "The Sales Pitch"
2. The Valgrind Framework
   - Dynamic Binary Instrumentation
   - Architecture
   - Framework Features
3. Creating a Valgrind Tool
   - Set Up a Valgrind Tool
   - Branchcount Example

The Valgrind Project

- Main authors and developers are Julian Seward and Nicholas Nethercote, University of Cambridge.
- Available under GPLv2.
- Supported for x86/x86-64/ppc32/ppc64 running Linux.
- Available at `http://www.valgrind.org`.

Valgrind Examples - Memcheck

- A bit precise memory checker.
  - Tracks undefined values.
  - Traces memory leaks.
  - Warns for reads/writes that are usually errors.

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C source

```
#include <stdbool.h>

int foo( bool b ) {
  if( b )
    return 0;
  else
   return 1;
}

int main( ) {
  bool b;
  return foo( b );
}
```

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  else
   return 1;
}

int main( ) {
  bool b;
  return foo( b );
}
```

Memcheck output

```
==16410== Conditional jump or move
          depends on uninitialised value(s)
==16410==    at 0x400454: foo
             (memcheck-example.c:4)
==16410==    by 0x40047B: main
             (memcheck-example.c:12)
```

Valgrind Examples - Cachegrind

- A cache profiler.
- Points out cache unfriendly code by annotations.

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C++ source

```
void scalarMul( int scalar, vector< vector<int> > matrix
                , size_t nRows, size_t nCols ) {

  for(int j=0; j < nCols; ++j )
    for(int i=0; i < nRows; ++i )
      matrix[i][j] *= scalar;
}
```

Valgrind Examples - Cachegrind

- A cache profiler.
- Points out cache unfriendly code by annotations.

C++ source

Cachegrind annotated code (100.000 rows, 100 cols, 2.3s)

```
      D1mr       D2mr
         .          .  void scalarMul( int scalar
         .          .    , vector< vector<int> > matrix
         0          0    , size_t nRows, size_t nCols ) {
         .          .
         0          0    for(int j=0; j < nCols; ++j )
         0          0      for(int i=0; i < nRows; ++i )
 9,999,999  9,963,671          matrix[i][j] *= scalar;
         0          0  }
```

Valgrind Examples - Cachegrind

- A cache profiler.
- Points out cache unfriendly code by annotations.

Alternative C++ Source

```
void scalarMul( int scalar, vector< vector<int> > matrix
                , size_t nRows, size_t nCols ) {

  for(int i=0; i < nRows; ++i )
    for(int j=0; j < nCols; ++j )
      matrix[i][j] *= scalar;
}
```

Valgrind Examples - Cachegrind

- A cache profiler.
- Points out cache unfriendly code by annotations.

Alternative C++ Source

Cachegrind annotated code (100.000 rows, 100 cols, 1.7)

```
    D1mr     D2mr
      .        .  void scalarMul( int scalar
      .        .     , vector< vector<int> > matrix
      0        0     , size_t nRows, size_t nCols ) {
      .        .
      0        0    for(int i=0; i < nRows; ++i )
      0        0      for(int j=0; j < nCols; ++j )
 650,001  649,999         matrix[i][j] *= scalar;
      0        0  }
```

Valgrind Examples - Other

- Callgrind - Feature rich profiling tool.
- Massif - Measures heap usage.
- Helgrind - Detects possible insufficient locking.

Commonality of the Tools

- **Dynamic**: Run-time analysis.
- **Binary**: Operates on the binary level.
- **Instrumentation**: *Normal* behavior of the program unmodified.

The Valgrind Framework

Valgrind is a framework for building dynamic binary instrumentation tools. Tool developers only need to focus on the analysis.

Why Dynamic Binary Instrumentation Matters

	Pro's	Cons
Dynamic	Precise Dynamic properties	Run-time cost Execution path analysis
Binary	Language independent Code coverage No source pollution	Platform dependent Traceableness

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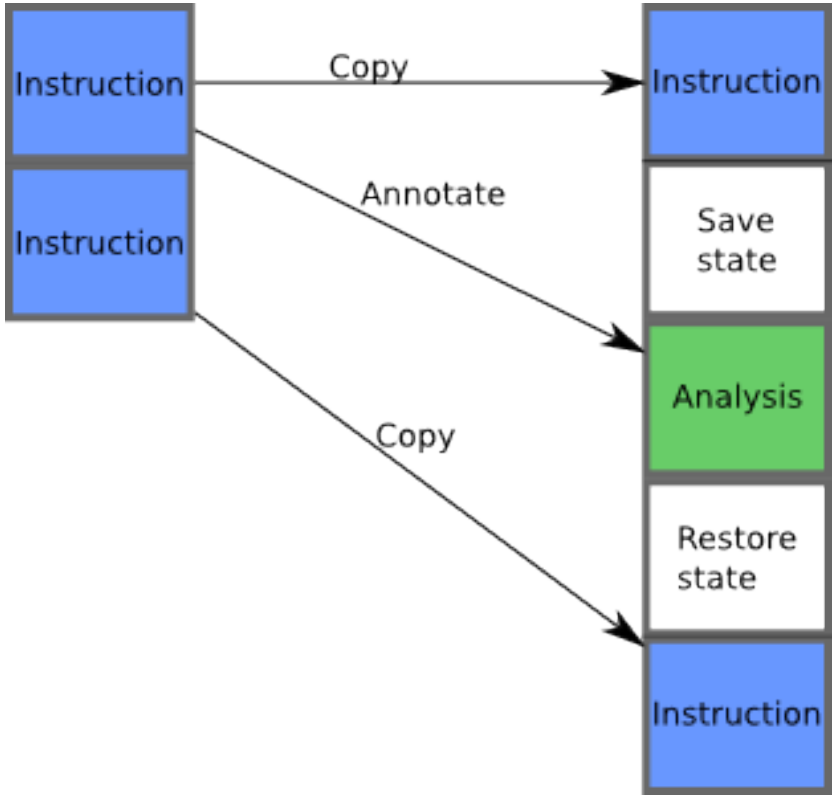
Dynamic analysis complements static analysis, just as binary analysis complements source analysis.

Binary Analysis Approaches

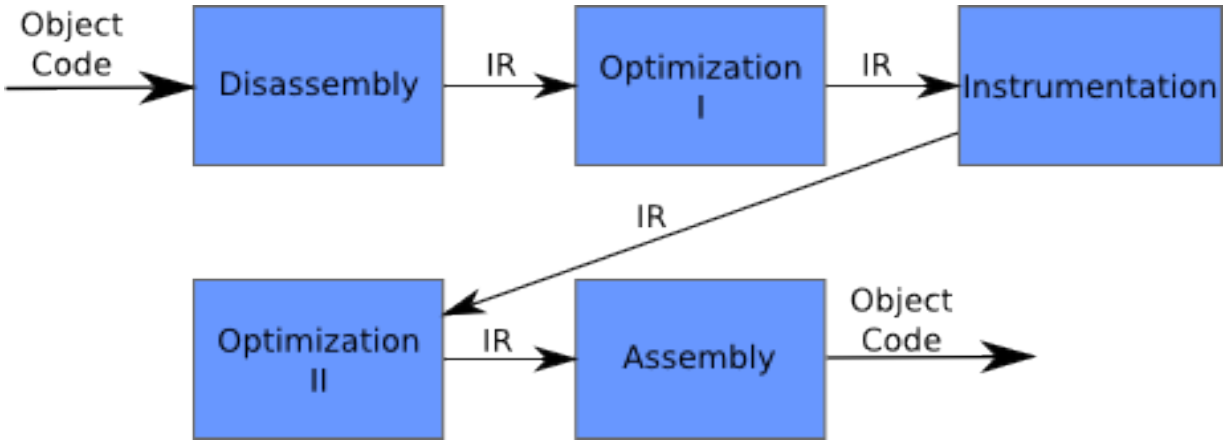
- Binary/Assembly difficult to analyze.
- Example: x86[-64]
  - Many opcodes with inconsistent behavior.
  - Complex addressing.
  - Implicit side-effects.
- Two options:
  - Copy and annotate
  - Disassemble and resynthesize

Copy and Annotate



- Verbatim copy program, generate annotations for analysis.
  - Efficient code stays efficient.
  - Analysis code unoptimized.

Disassemble And Resynthesize



- Transform program to IR, analyze and transform back to executable code.
- Valgrind based on disassemble and resynthesize.
- Similar to Java's JVM.
  - Compiles to a virtual RISC CPU. All client code runs on this CPU.
  - Conventional compiler optimizations.
- Disassemble and resynthesize efficient for heavyweight instrumentation.

Unboxing Example - Introduction

Goal of the Example

This example demonstrates the process the disassemble and resynthesize of a plain C function by Valgrind. Memcheck performs the instrumentation.

Code convention

- **Virtual registers** in upper case (EBP, EAX, ESP).
- **Physical registers** in lower case (%ebp, %eax, %esp).
- **Temporary registers** are in the form t*n*.

Unboxing Example - Introduction

- In the Essential Haskell Compiler[1] integers are unboxed.
- Pointer alignment at 32 or 64 bits, last 2 or 3 bits always zero.
- Left-shift and set the LSB to distinguish unboxed value.

[1] Atze Dijkstra. EHC Web. `http://www.cs.uu.nl/wiki/Ehc/WebHome`, 2004.

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C code to box an integer

```
int box(int ubxInt)
{
  return (ubxInt << 1) | 0x01;
}
```

[1] Atze Dijkstra. EHC Web. http://www.cs.uu.nl/wiki/Ehc/WebHome, 2004.

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C code to box an integer

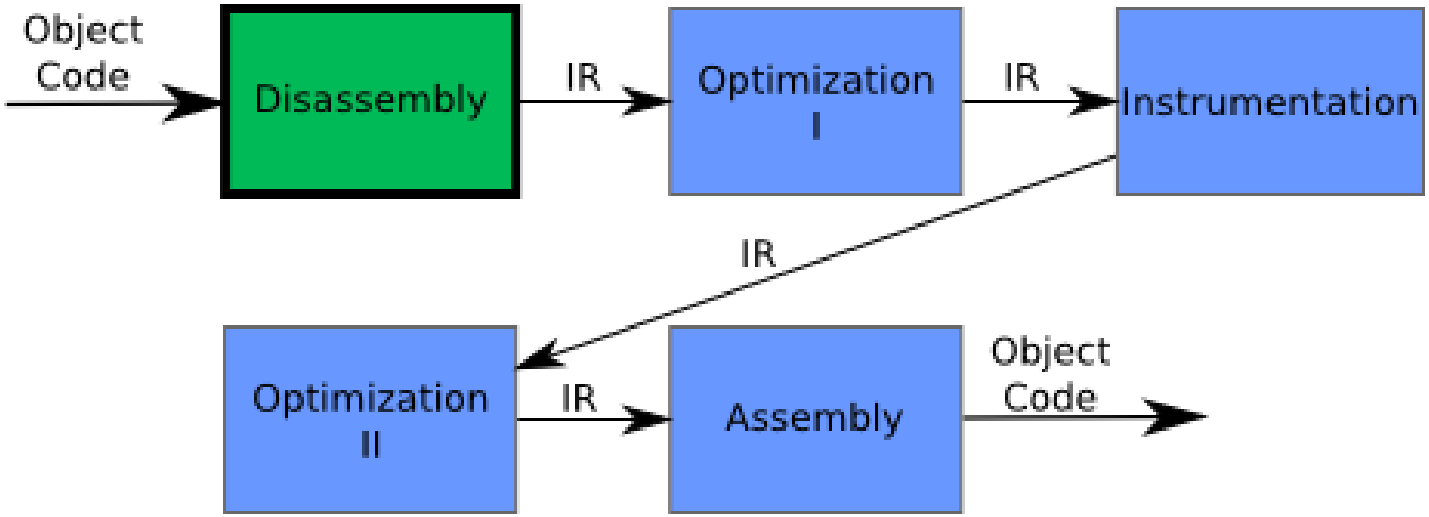
```
int box(int ubxInt)
{
  return (ubxInt << 1) | 0x01;
}
```

ASM output (GCC -O0)

```
...
mov     0x8(%ebp),%eax
add     %eax,%eax
or      $0x1,%eax
...
```

[1] Atze Dijkstra. EHC Web. http://www.cs.uu.nl/wiki/Ehc/WebHome, 2004.

Unboxing Example - Disassembly



Purpose:

- Introduces the virtual RISC CPU.
- Makes side-effects explicit.

Unboxing Example - Disassem

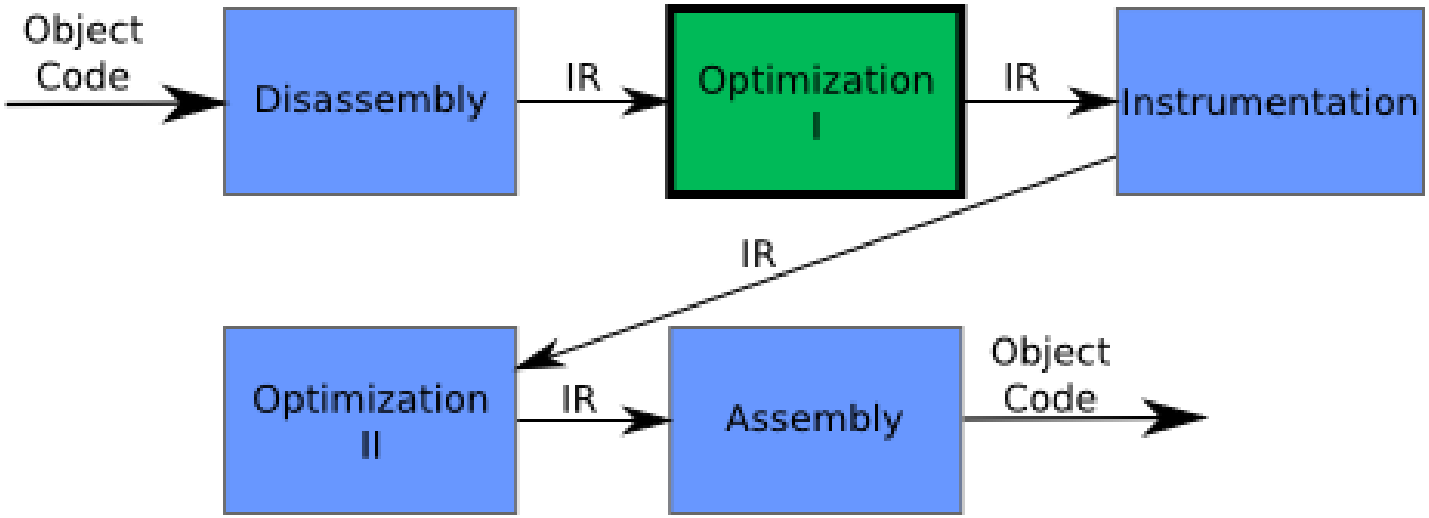
Object code

```
...
mov     0x8(%ebp),%eax
add     %eax,%eax
or      $0x1,%eax
...
```

IR

```
------ IMark(0x8048347, 3) ------
PUT(EIP) = 0x8048347:I32
t19 = Add32(GET:I32(EBP),0x8:I32)
PUT(EAX) = LDle:I32(t19)
------ IMark(0x804834A, 2) ------
PUT(EIP) = 0x804834A:I32
t22 = GET:I32(EAX)
t21 = GET:I32(EAX)
t20 = Add32(t22,t21)
PUT(CC_OP) = 0x3:I32
PUT(CC_DEP1) = t22
PUT(CC_DEP2) = t21
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t20
------ IMark(0x804834C, 3) ------
PUT(EIP) = 0x804834C:I32
t25 = GET:I32(EAX)
t24 = 0x1:I32
t23 = Or32(t25,t24)
PUT(CC_OP) = 0xF:I32
PUT(CC_DEP1) = t23
PUT(CC_DEP2) = 0x0:I32
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t23
```

Unboxing Example - Optimization 1



- Purpose: Optimize IR for easier instrumentation.
- Conventional compiler optimizations.
  - Dead code elimination.
  - Copy propagation.
  - Constant folding.
  - Common sub-expression elimination.

IR

```
------ IMark(0x8048347, 3) ------
PUT(EIP) = 0x8048347:I32
t19 = Add32(GET:I32(EBP),0x8:I32)
PUT(EAX) = LDle:I32(t19)
------ IMark(0x804834A, 2) ------
PUT(EIP) = 0x804834A:I32
t22 = GET:I32(EAX)
t21 = GET:I32(EAX)
t20 = Add32(t22,t21)
PUT(CC_OP) = 0x3:I32
PUT(CC_DEP1) = t22
PUT(CC_DEP2) = t21
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t20
------ IMark(0x804834C, 3) ------
PUT(EIP) = 0x804834C:I32
t25 = GET:I32(EAX)
t24 = 0x1:I32
t23 = Or32(t25,t24)
PUT(CC_OP) = 0xF:I32
PUT(CC_DEP1) = t23
PUT(CC_DEP2) = 0x0:I32
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t23
```

Optimized IR

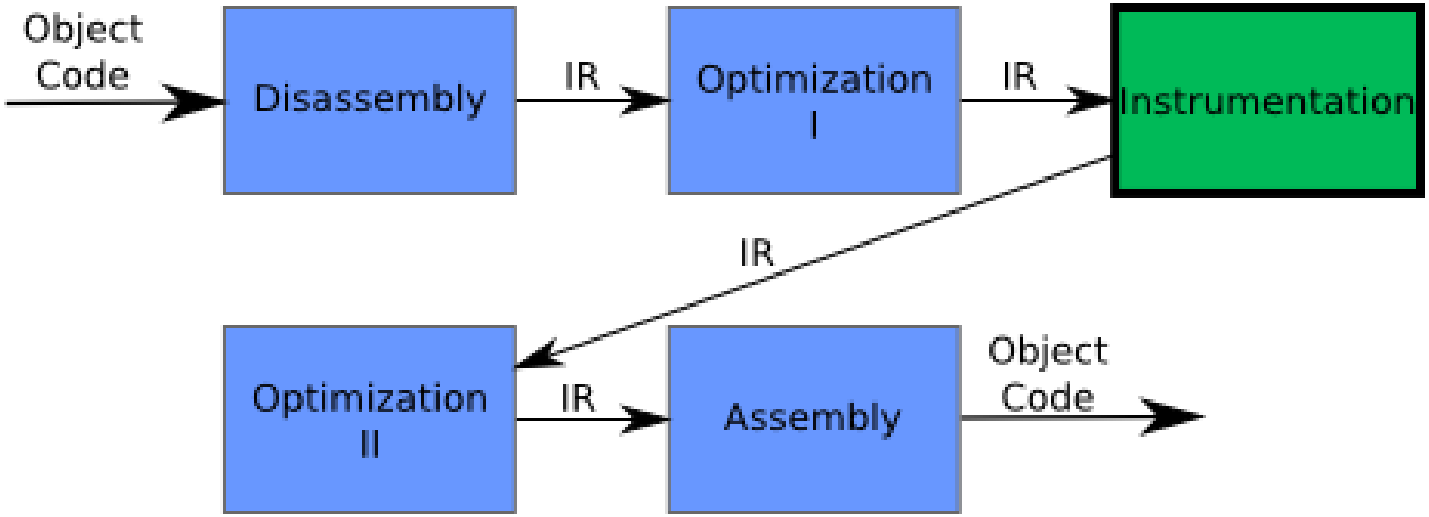
```
------ IMark(0x8048347, 3) ------
PUT(EIP) = 0x8048347:I32
t48 = Add32(t45,0x8:I32)
t50 = LDle:I32(t48)
------ IMark(0x804834A, 2) ------

t20 = Shl32(t50,0x1:I8)

------ IMark(0x804834C, 3) ------

t23 = Or32(t20,0x1:I32)
PUT(CC_OP) = 0xF:I32
PUT(CC_DEP1) = t23
PUT(CC_DEP2) = 0x0:I32
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t23
```

Unboxing Example - Instrumentation



- Purpose: Add analysis to the executable.
- Phase not performed by framework.

Unboxing Example - Instru

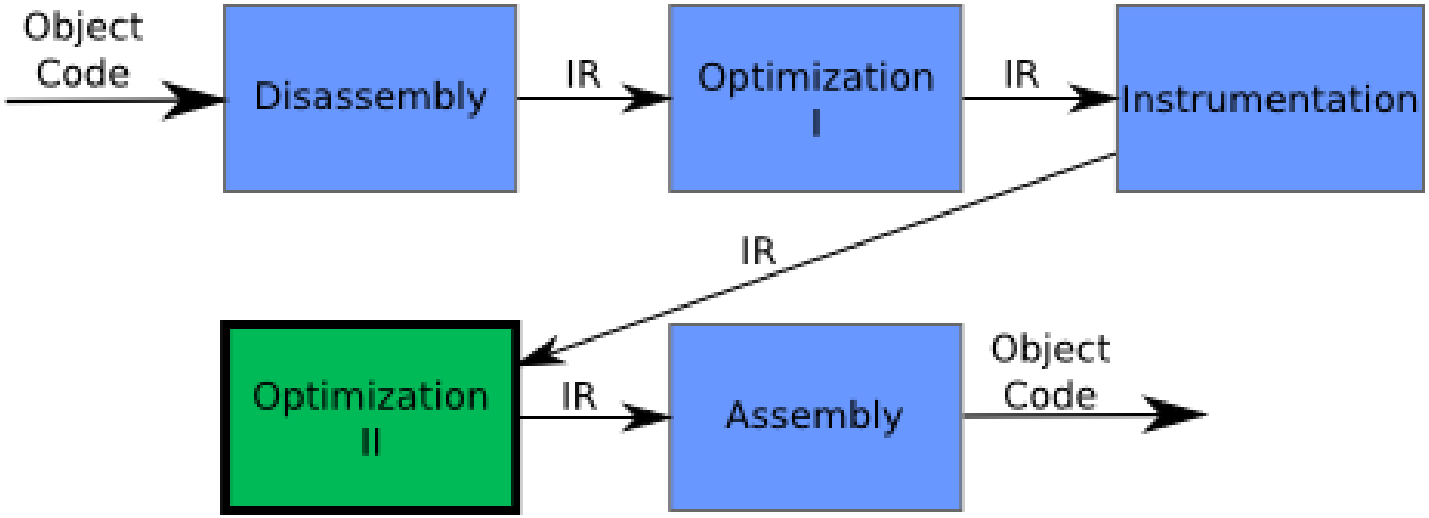
Optimized IR

```
------ IMark(0x8048347, 3) ------
PUT(EIP) = 0x8048347:I32
t48 = Add32(t45,0x8:I32)
t50 = LDle:I32(t48)
------ IMark(0x804834A, 2) ------
t20 = Shl32(t50,0x1:I8)
------ IMark(0x804834C, 3) ------
t23 = Or32(t20,0x1:I32)
PUT(CC_OP) = 0xF:I32
PUT(CC_DEP1) = t23
PUT(CC_DEP2) = 0x0:I32
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t23
```

Instrumented IR (Memcheck)

```
------ IMark(0x8048347, 3) ------
PUT(EIP) = 0x8048347:I32
t108 = Left32(t106)
t48 = Add32(t45,0x8:I32)
t109 = CmpNEZ32(t108)
t112 = DIRTY 1:I1 RdFX-gst(16,4)...
t50 = LDle:I32(t48)
------ IMark(0x804834A, 2) ------
t113 = CmpNEZ8(0x0:I8)
t114 = 1Sto32(t113)
t115 = Shl32(t112,0x1:I8)
t116 = Or32(t115,t114)
t118 = Or32(t115,t114)
t20 = Shl32(t50,0x1:I8)
------ IMark(0x804834C, 3) ------
t119 = Not32(0x1:I32)
t121 = Not32(t20)
t122 = Or32(t121,t118)
t123 = And32(t122,t119)
t127 = And32(t118,t123)
t23 = Or32(t20,0x1:I32)
PUT(CC_OP) = 0xF:I32
PUT(CC_DEP1) = t23
PUT(CC_DEP2) = 0x0:I32
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t23
```

Unboxing Example - Optimization 2



- Purpose: Optimize the instrumentation code.

Instrumented IR (Memcheck)

```
------ IMark(0x8048347, 3) ------
PUT(EIP) = 0x8048347:I32
t108 = Left32(t106)
t48 = Add32(t45,0x8:I32)
t109 = CmpNEZ32(t108)
t112 = DIRTY 1:I1 RdFX-gst(16,4)...
t50 = LDle:I32(t48)
------ IMark(0x804834A, 2) ------
t113 = CmpNEZ8(0x0:I8)
t114 = 1Sto32(t113)
t115 = Shl32(t112,0x1:I8)
t116 = Or32(t115,t114)
t118 = Or32(t115,t114)
t20 = Shl32(t50,0x1:I8)
------ IMark(0x804834C, 3) ------
t119 = Not32(0x1:I32)
t121 = Not32(t20)
t122 = Or32(t121,t118)
t123 = And32(t122,t119)
t127 = And32(t118,t123)
t23 = Or32(t20,0x1:I32)
PUT(CC_OP) = 0xF:I32
PUT(CC_DEP1) = t23
PUT(CC_DEP2) = 0x0:I32
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t23
```

Optimized instrumented IR

```
------ IMark(0x8048347, 3) ------
PUT(EIP) = 0x8048347:I32

t48 = Add32(t45,0x8:I32)

t112 = DIRTY 1:I1 RdFX-gst(16,4) ...
t50 = LDle:I32(t48)
------ IMark(0x804834A, 2) ------



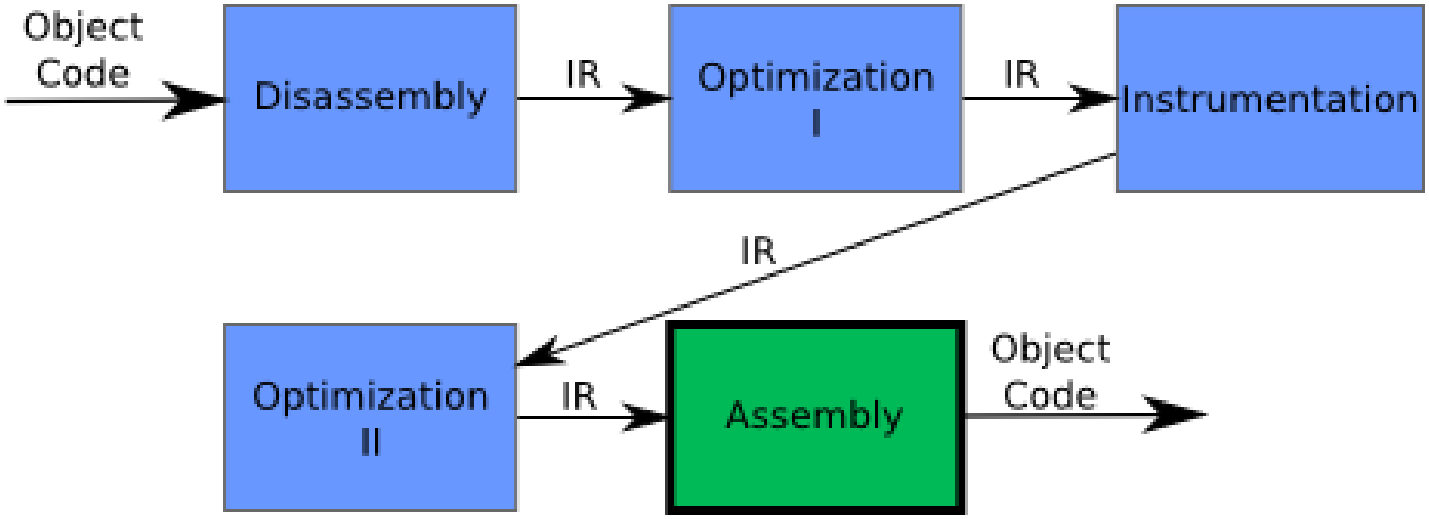
t112 = Shl32(t111,0x1:I8)



t20 = Shl32(t50,0x1:I8)
------ IMark(0x804834C, 3) ------

t121 = Not32(t20)
t122 = Or32(t121,t115)
t123 = And32(t122,0xFFFFFFFE:I32)
t125 = And32(t115,t123)
t23 = Or32(t20,0x1:I32)
PUT(CC_OP) = 0xF:I32
PUT(CC_DEP1) = t23
PUT(CC_DEP2) = 0x0:I32
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t23
```

Unboxing Example - Assembly



- Purpose: Convert IR back to machine instructions.
- Select proper instructions.
- Allocate registers.
- Object code stored and executed.

Unboxing Example - Assembly

Optimized instrumented IR

```
------ IMark(0x8048347, 3) ------
PUT(EIP) = 0x8048347:I32
t48 = Add32(t45,0x8:I32)
t112 = DIRTY 1:I1 RdFX-gst(16,4) ...
t50 = LDle:I32(t48)
------ IMark(0x804834A, 2) ------
t112 = Shl32(t111,0x1:I8)
t20 = Shl32(t50,0x1:I8)


------ IMark(0x804834C, 3) ------
t121 = Not32(t20)
t122 = Or32(t121,t115)
t123 = And32(t122,0xFFFFFFFE:I32)
t125 = And32(t115,t123)
t23 = Or32(t20,0x1:I32)
PUT(CC_OP) = 0xF:I32
PUT(CC_DEP1) = t23
PUT(CC_DEP2) = 0x0:I32
PUT(CC_NDEP) = 0x0:I32
PUT(EAX) = t23
```

Object code

```
movl $0x8048347,0x3C(%ebp)
leal 0x8(%ebx),%esi
movl %esi,%eax
call 0x38006BB0
movl %eax,%edi

shll $1,%edi
movl (%esi),%edx
shll $1,%edx
movl %edx,%esi

notl %esi
orl  %edi,%esi
andl $0xFFFFFFFE,%esi
andl %esi,%edi
orl  $0x1,%edx
movl $0xF,0x20(%ebp)
movl %edx,0x24(%ebp)
movl $0x0,0x28(%ebp)
movl $0x0,0x2C(%ebp)
movl %edx,(%ebp)
```

Framework Features

Function overriding

- Functions can be overridden by a tool.
- Allows action on specific methods.
- Function can call the replaced function (wrapping).
- Internal memory management depends on function overriding.

Events

- Various call-back hooks are available.
- Control over memory allocations and stack usage.
- Essential for system calls support.
- Examples:
  - pre_mem_read, pre_mem_write, post_mem_write
  - new_mem_mmap, die_mem_munmap, new_mem_remap
  - new_mem_stack, die_mem_stack

Client requests

- Executable code can pass information to a Valgrind Tool.
- Request translates to no-op when native executed.
- Examples:
  - Set memory valid for memcheck.
  - Annotate code as self modifying.
  - Start/Stop instrumenting.

Creating a Valgrind Tool

5 Simple Steps

1. Download Valgrind source.
2. Copy the *none* directory.
3. Come up with a cool name and abbreviation.
4. Write 4 C functions.
5. `./configure && make && make install`

4 Simple Functions (And 1 Macro)

C Interface to Valgrind

```
// Macro to register init function
VG_DETERMINE_INTERFACE_VERSION(xyz_pre_clo_init)

// Function to register other 3 functions
static void xyz_pre_clo_init(void);

// Initialize
static void xyz_post_clo_init(void);

// Instrumentation function
static IRSB* xyz_instrument(VgCallbackClosure* closure,
                            IRSB* bbIn,
                            VexGuestLayout* layout,
                            VexGuestExtents* vge,
                            IRType gWordTy, IRType hWordTy);

// Clean up / output report
static void xyz_fini(Int exitcode);
```

Example - Branchcount Instrument Snipplet

Instrumentation code

```
IRSB* bbOut = deepCopyIRSB(bbIn);
switch( bbOut->jumpkind ) {

  case Ijk_Boring: {
    if( !exprIsConst( bbOut->next ) ) {

      // it is a indirect jump
      //
      di = unsafeIRDirty_0_N( 0, "countJumpIndir",
                              VG_(fnptr_to_fnentry)
                                ( &countJumpIndir ),
                              mkIRExprVec_0() );
      addStmtToIRSB( bbOut, IRStmt_Dirty(di) );
    }
    break;
  }
...
```

Example - Branchcount Instrument Snipplet

Instrumentation code

Example output

```
==14425== Jumps direct
==14425==   counted:          500,000,000 ( 14%)
==14425== Jumps indirect
==14425==   counted:          500,000,000 ( 14%)
==14425== Calls direct
==14425==   counted:          500,000,000 ( 14%)
==14425== Calls indirect
==14425==   counted:          500,000,000 ( 14%)
==14425== Returns
==14425==   counted:          1,000,000,000 ( 28%)
==14425== Conditionals
==14425==   counted:          500,000,000 ( 14%)
==14425== Other
==14425==   counted:          0 (  0%)
```

Conclusion

- Valgrind is a framework for dynamic binary instrumentation.
- 5 tools are distributed with the framework:
  - Memcheck.
  - Cachegrind.
  - Callgrind.
  - Massif.
  - Helgrind.
- Valgrind is based on disassemble and resynthesize.
- Developers can just focus on the analysis, very little boiler plate code is required.

Developer Resources

- Source code available at `http://www.valgrind.org/downloads/current.html`.
- Available on Linux for x86/x86-64/ppc32/ppc64.
- Source heavily documented:
  - Virtual registers: `VEX/pub/libvex_guest_<arch>.h`.
  - Options for optimizations: `VEX/pub/libvex.h`.
  - IRSB Struct: `VEX/pub/libvex_ir.h`.
- Questions? Try the valgrind-developer mailing list.

Happy Instrumenting!