Security Research & Development with LLVM

Andrew R. Reiter

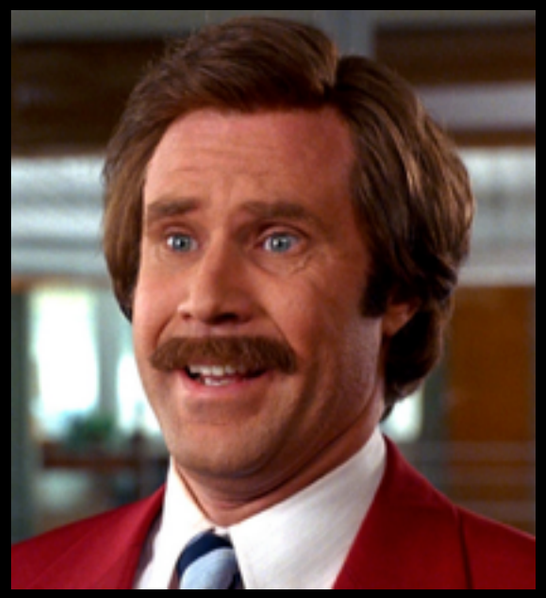
OPCDE 2017

Part of longer term research effort between speaker and Jared Carlson

Bio

- Principal Security Researcher, Veracode (USA)
- Past: vuln research, exploit dev, malware analysis, OS dev, RF work
- Ancient history: w00w00, HERT, FreeBSD

"…standing on the shoulders of giants" — Newton



Obvious trend?

- Increase in mingling: academia and "security scene"
- Demand for increased rigor in security research
- Thus increasingly specialized….
- leading to a desire for reusability & modularity in security research|dev

1 example of this trend… LLVM in R&D

Code Share

- Some *small*, **basic** example codes
- Introduce APIs and workflow, so can…
- More easily read research code for *meaning*

https://github.com/roachspray/opcde2017

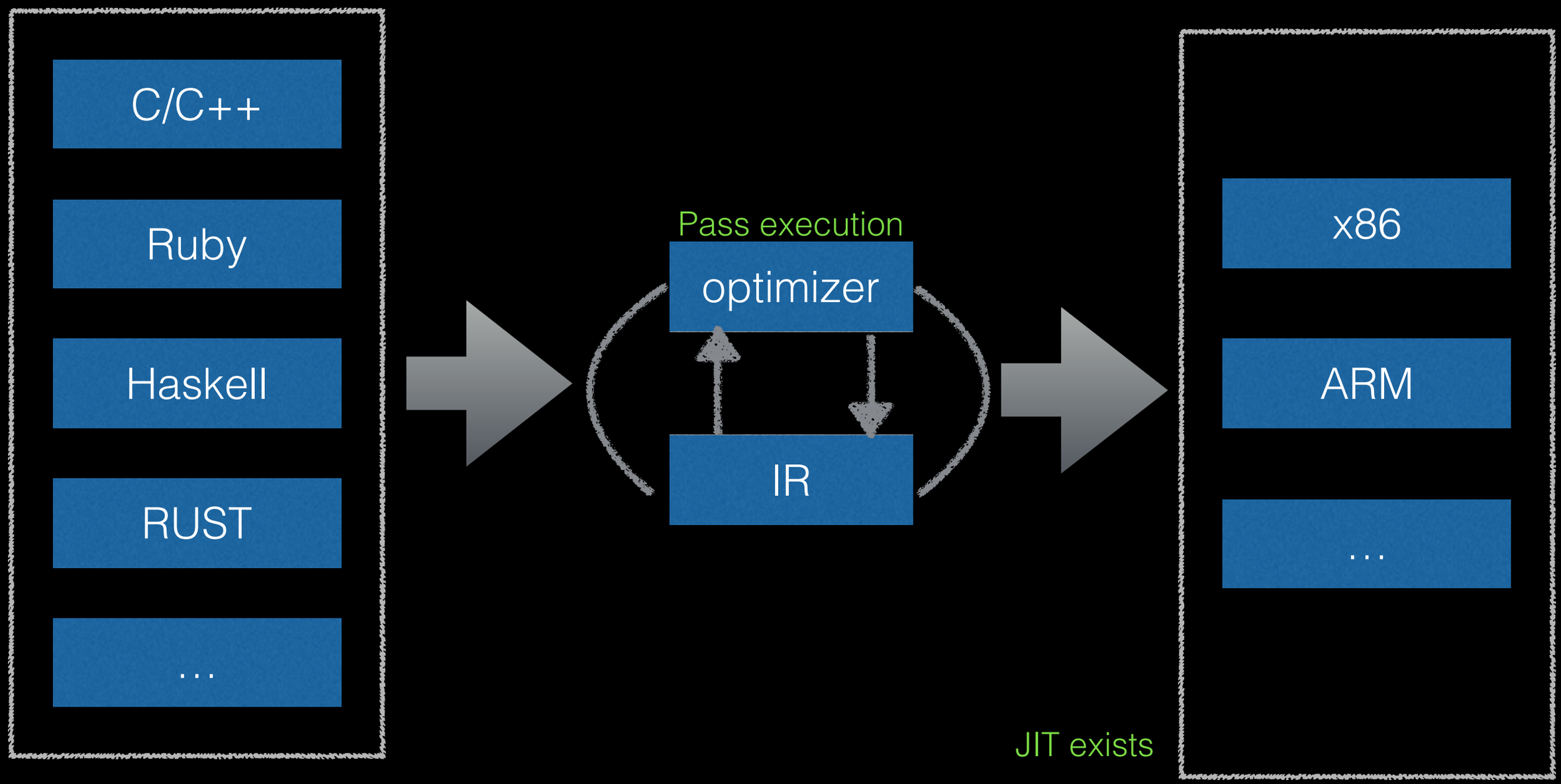
Mostly look at: intflip, npassert, comminute

LLVM Compiler Infrastructure

- Modern compiler research:
  - Optimization
  - Program analysis research
- Started UIUC in early 2000s: Vikram Adve, Chris Lattner
- Open source — the core is the community
- (Major) Corporate support

http://llvm.org/pubs/2002-12-LattnerMSThesis.html

High Level Architecture



Intermediate Representation

- Static Single Assignment (SSA)
- Strongly typed
- Architecture and Language agnostic
- 3 forms:
    1. in-memory
    2. on-disk bitcode (.bc)
    3. on-disk human readable (.ll) (looks assemblerish)

Core API

- Stable/robust core provides:
    - IR generation and manipulation
    - Analysis and optimization of IR
    - Machine code generation
- Some (non-essential) APIs in research mode / unstable
- C++11 and C++14

Provided Utilities

- clang: native C/C++/Obj-C compiler
- opt: executes analysis & optimization passes on IR
- llvm-dis: bitcode IR to human readable IR
- klee: symbolic execution

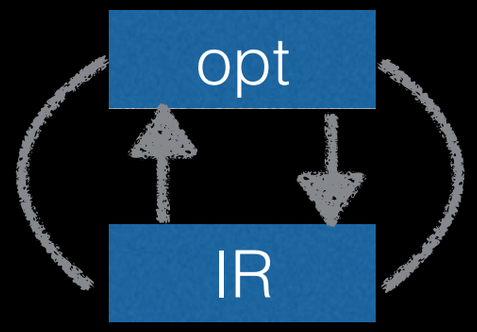
```
[awr@anathema:~]$ vi foo.c
[awr@anathema:~]$ clang-3.9 -emit-llvm -o foo.bc -c foo.c
[awr@anathema:~]$ llvm-dis-3.9 -o=foo.ll foo.bc
```

- Many others *

* http://llvm.org/docs/CommandGuide/

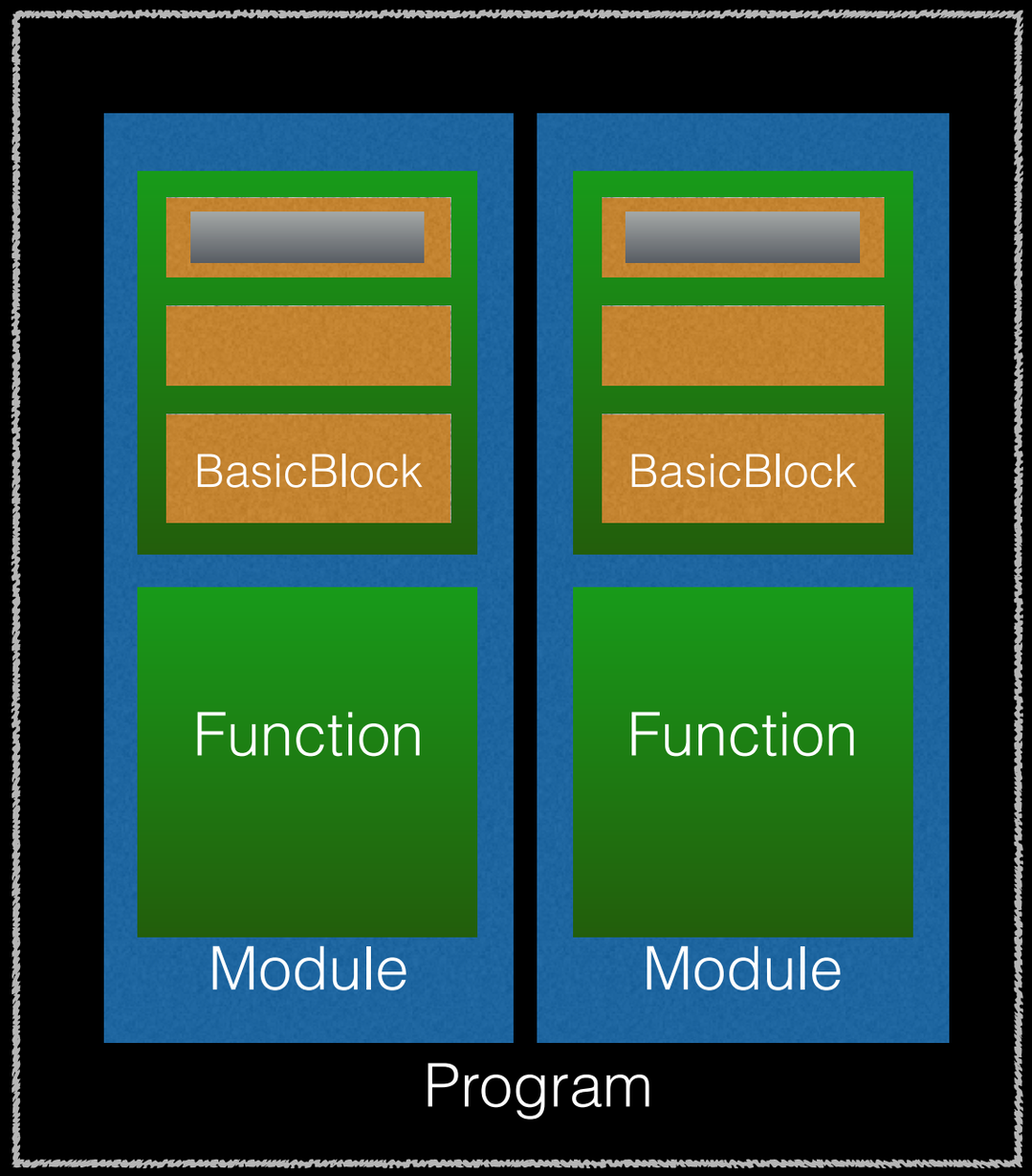
Passes are King

- Mapping IR to IR
- Many provided by LLVM; part of framework
- Build your own for fun and/or profit
- Either:
    - Analysis passes ~ read-only
    - Transform passes ~ read/write
- **Chain** ‘em — analyze, then use results in another



Pass Impl Types

- Types*:
  - ModulePass
  - FunctionPass or MachineFunctionPass
  - BasicBlockPass
  - LoopPass
  - RegionPass
  - CallGraphSCCPass
- Atleast implement *runOnTYPE() function*



*The code share has skeletons of each

Pass Rules Everything Around Me, P.R.E.A.M.

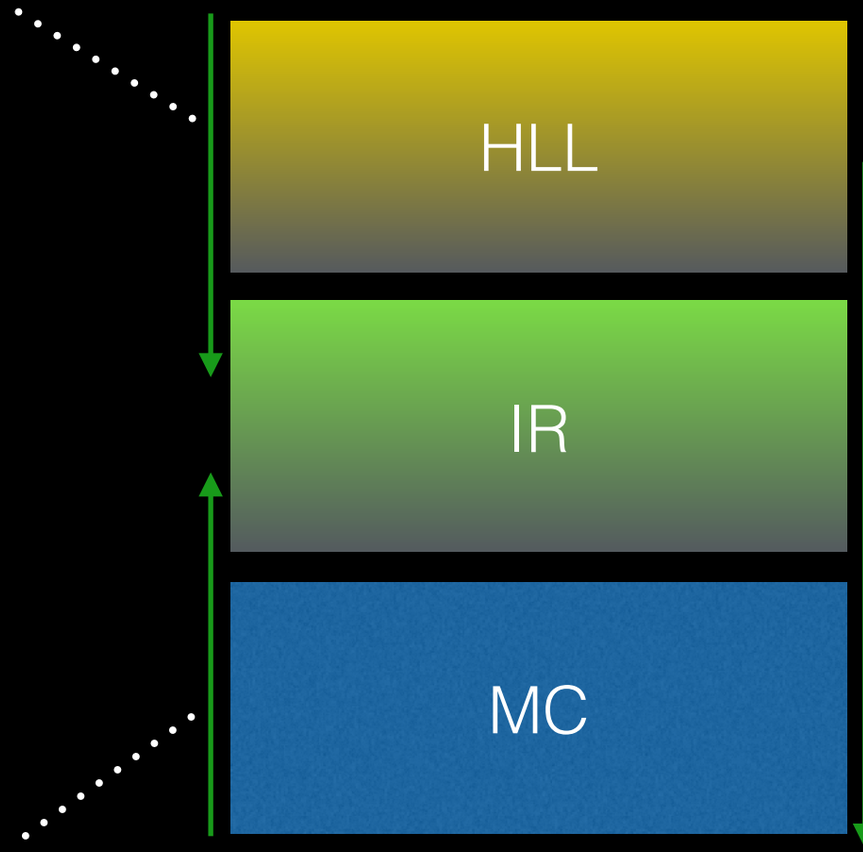
- Different pass type => different restrictions*

1. Determine the needs of your analysis|transform
2. Find Pass type supporting your needs.
3. Use “Principle of least privilege” mindset.

*Find the restrictions listed: http://llvm.org/docs/WritingAnLLVMPass.html

Security R&D + LLVM

- static analysis
- proving properties
- symbolic exec
- reverse engineering



- fuzzing
- harden code
- code obfuscation

Quarkslab

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Carnegie
Mellon
University

Penn

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OF UTAH

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spec

université
PARIS-SACLAY

UNIVERSITY
OF TWENTE.

galois

FACULTAS ARTIS INFORMATICÆ
UNIVERSITAS MASARYKIANA

SCIENTIA IMPERII DECUS ET TUTAMEN

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

MASSACHUSETTS
INSTITUTE OF TECHNOLOGY

informatics mathematics
Inria

VUSec

institute
IMdea

TRAIL OF BITS

UNIVERSITÉ
Grenoble
Alpes

I wanted to list everything in this slide deck, but too much… I have a listing below

https://github.com/roachspray/opcde2017/blob/master/projects.md

- Please send me additions

Vellvm: Verified LLVM

- Model syntax and semantics of LLVM IR so as to…
- Reason about code expressed in IR in order to…
- Prove properties about LLVM passes in Coq *
- OCaml extracted, ran unit tests validating model

Recently revived!

* https://coq.inria.fr/

Software Analysis Workbench (SAW)

|galois|

- Formal verification via equivalency checking
- Map IR to logical form (formal model)
- Uses multiple SMT/SAT solvers
- Able to ingest bitcode (.bc) file

http://saw.galois.com/

Mc Sema | Remill | VMill

- Lift machine code (data + code) to IR
    - instruction lift
    - data inclusion and making LLVM modules

in order to perform:

- Recompilation of MC
- Retargeting of MC to another arch
- Symbolic execution of IR (e.g. for fuzzing)
- Snapshot native->symbolic exec w/ memory

https://blog.trailofbits.com/2015/07/15/how-we-fared-in-the-cyber-grand-challenge/
https://github.com/trailofbits/mcsema
https://github.com/trailofbits/remill

Sanitizers

- Hybrid dynamic/static:
    - Statically instrument IR
    - Link with library to catch issues at RT

- AddressSanitizer: catch UAF, UAR, etc 
- DataFlowSanitizer: implement own taint analysis
- TypeSan: C++ cast errors 

https://github.com/google/sanitizers
https://github.com/vusec/typesan

Fuzzing

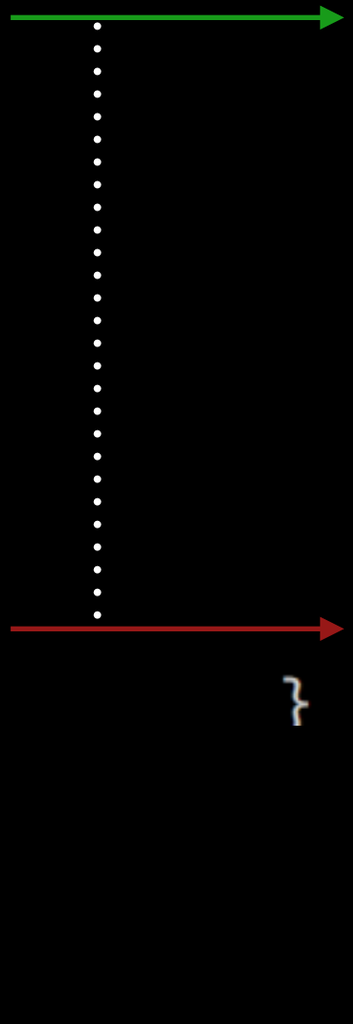
- LibFuzzer:
    - evolutionary, in-process guided fuzzer
    - *part* of LLVM project
- Improving action of existing fuzzers:
    - lafindel's compare splitting passes
    - TokenCap: find magics/fuzz roadblocks & remove

More…

- Application hardening
- Translation to formal languages
- Software resiliency
- … ok I'll stop and move forward.. but please view the list on github and check the projects out!

Ok..to some code

Motivate: Ultra-Contrived C sensitive leak



```
char *p;
struct addrinfo hints, *result;

p = getpass("enter passwd: ");
/* l.v. p is now tainted with sensitive data */
memset(&hints, 0, sizeof(struct addrinfo));
hints.ai_family = AF_UNSPEC;
hints.ai_socktype = SOCK_DGRAM;
hints.ai_flags = 0;
hints.ai_protocol = 0;
/* leak password via getaddrinfo() DNS lookup. contrived af. */
(void)getaddrinfo(p, "http", &hints, &result);
}
```

```
[awr@anathema tests] clang-3.9 -g -emit-llvm -o NSDL001.bc -c NSDL001.c
```

```
define void @leaks_passwd() #0 !dbg !18 {
  %1 = alloca i8*, align 8
  %2 = alloca %struct.addrinfo, align 8
  %3 = alloca %struct.addrinfo*, align 8
  call void @llvm.dbg.declare(metadata i8** %1, metadata !22, metadata !25), !dbg !26
  call void @llvm.dbg.declare(metadata %struct.addrinfo* %2, metadata !27, metadata !25), !dbg !58
  call void @llvm.dbg.declare(metadata %struct.addrinfo** %3, metadata !59, metadata !25), !dbg !60
  %4 = call i8* @getpass(i8* getelementptr inbounds ([15 x i8], [15 x i8]* @.str, i32 0, i32 0)),
  store i8* %4, i8** %1, align 8, !dbg !62
  %5 = bitcast %struct.addrinfo* %2 to i8*, !dbg !63
  call void @llvm.memset.p0i8.i64(i8* %5, i8 0, i64 48, i32 8, i1 false), !dbg !63
  %6 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %2, i32 0, i32 1, !dbg !64
  store i32 0, i32* %6, align 4, !dbg !65
  %7 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %2, i32 0, i32 2, !dbg !66
  store i32 2, i32* %7, align 8, !dbg !67
  %8 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %2, i32 0, i32 0, !dbg !68
  store i32 0, i32* %8, align 8, !dbg !69
  %9 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %2, i32 0, i32 3, !dbg !70
  store i32 0, i32* %9, align 4, !dbg !71
  %10 = load i8*, i8** %1, align 8, !dbg !72
  %11 = call i32 @getaddrinfo(i8* %10, i8* getelementptr inbounds ([5 x i8], [5 x i8]* @.str.1, i32
```

No mem2reg run, so let's..

After mem2reg

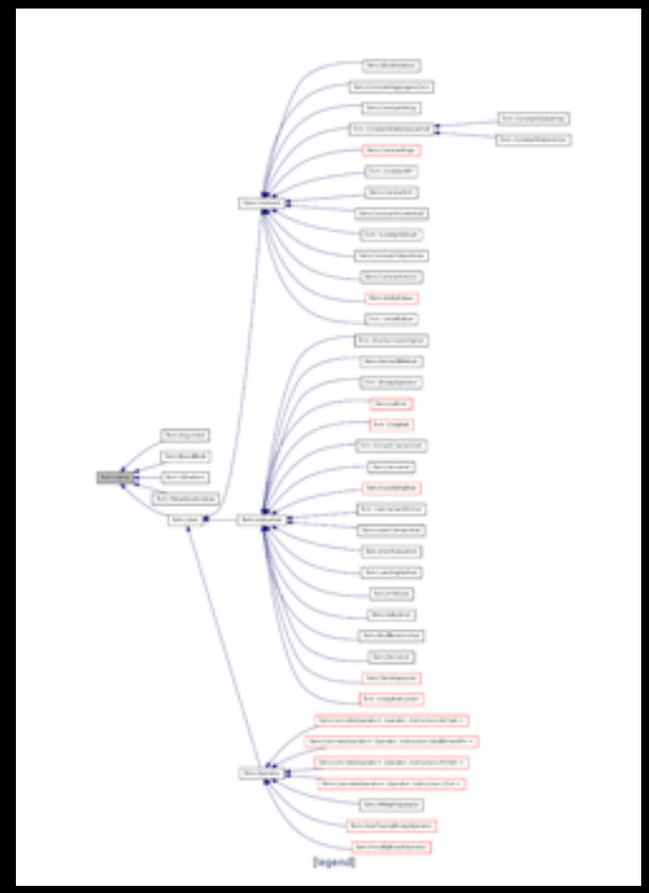
```
[awr@anathema tests] opt-3.9 -mem2reg -o NSDL001.bc < NSDL001.bc
[awr@anathema tests]
```

```
define void @leaks_passwd() #0 {
  %1 = alloca %struct.addrinfo, align 8
  %2 = alloca %struct.addrinfo*, align 8
  %3 = call i8* @getpass(i8* getelementptr inbounds ([15 x i8], [15 x i8]* @.str, i32 0, i32 0))
  %4 = bitcast %struct.addrinfo* %1 to i8*
  call void @llvm.memset.p0i8.i64(i8* %4, i8 0, i64 48, i32 8, i1 false)
  %5 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %1, i32 0, i32 1
  store i32 0, i32* %5, align 4
  %6 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %1, i32 0, i32 2
  store i32 2, i32* %6, align 8
  %7 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %1, i32 0, i32 0
  store i32 0, i32* %7, align 8
  %8 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %1, i32 0, i32 3
  store i32 0, i32* %8, align 4
  %9 = call i32 @getaddrinfo(i8* %3, i8* getelementptr inbounds ([5 x i8], [5 x i8]* @.str.1, i32 0, i
```

Just using the value as the arg

Value class

- Base class for all operands, but others as well
  - *Function*
  - *Module*
  - *Instruction (BranchInst, AllocaInst..)*
- *User* list
- *Value* has a *Type*



http://llvm.org/docs/doxygen/html/classllvm_1_1Value.html

User in action from mpskel

```
for (auto &F : M) { /* Iterate through all functions in this module */
  std::string fname = "not named";
  if (F.hasName()) {
    fname = F.getName().str();
  }
  if (F.user_empty()) { // If no uses, don't look further.
    errs() << "Function (" << fname << ") not used.\n";
    continue;
  }
  errs() << "Listing uses for function (" << fname << ")\n";
  for (auto uit = F.user_begin(); uit != F.user_end(); ++uit) {
    User *u = *uit;
    errs() << "   ";
    std::string pn = "";
    if (isa<CallInst>(u) || isa<InvokeInst>(u)) { // Is this use a Call or Invoke instruction?
      CallSite cs(dyn_cast<Instruction>(u)); // It is, so let's use the common class CallSite
      Function *caller = cs.getParent()->getParent(); // Instruction in a BasicBlock in a Function.
      if (caller->hasName()) {
        pn = caller->getName().str();
      } else {
        pn = "not named";
      }
      errs() << pn << ": ";
    }
    u->dump();
```

```
[awr@anathema mpskel] opt-3.9 -load built/MPSkel.so -mem2reg -mpskel ../comminute/tests/NSDL001.bc 1> /dev/null
...
Listing uses for function (getpass)
   leaks_passwd:   %3 = call i8* @getpass(i8* getelementptr inbounds ([15 x i8], [15 x i8]* @.str, i32 0, i32 0)
...
Listing uses for function (getaddrinfo)
   leaks_passwd:   %9 = call i32 @getaddrinfo(i8* %3, i8* getelementptr inbounds ([5 x i8], [5 x i8]* @.str.1, i
%struct.addrinfo** %2), !dbg !71
```

Goal: Basic tool, meant to support multiple analyses; start with:

A. find leaking of sensitive data

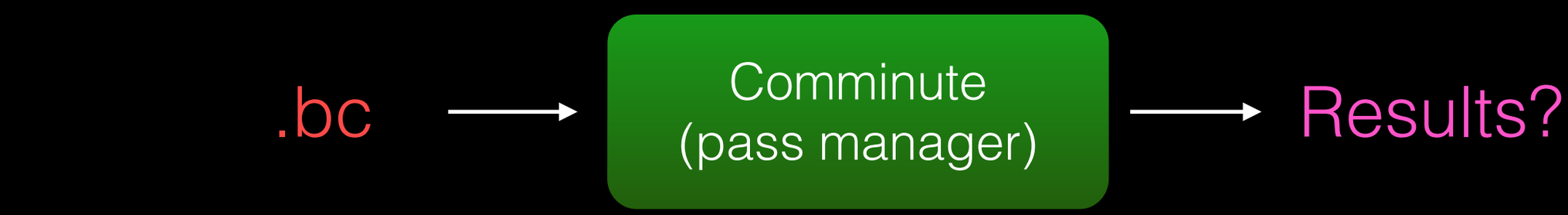
B. find leaking of file descriptors

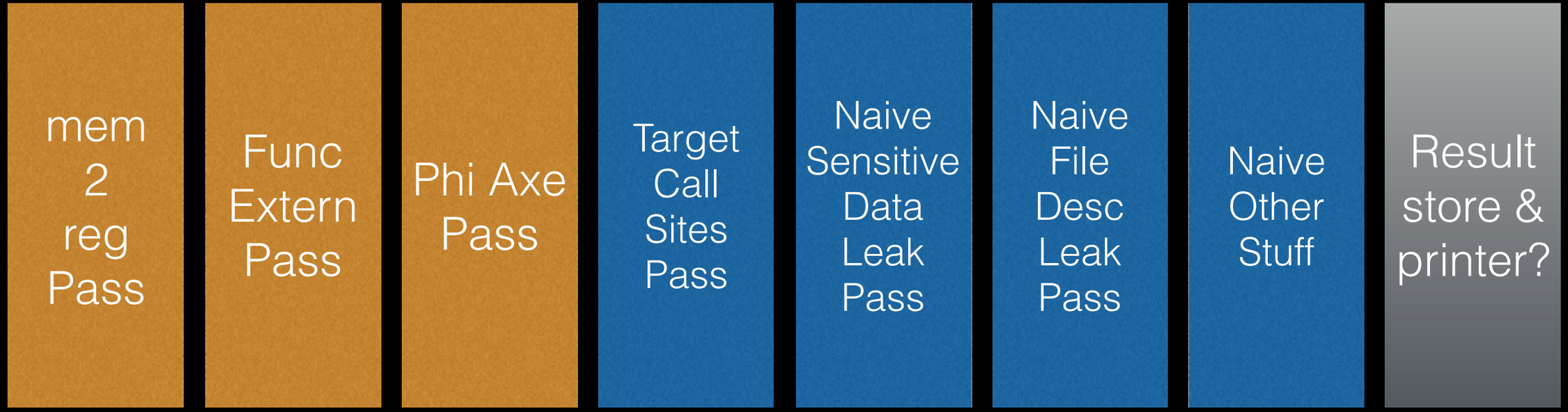
C. use of “bad” functions

Method:

- transform code to forms easier to deal with
- find sources of such data
- find sinks of such data
- attempt some sort of reachability analysis
- pass manager to control running of passes and be a front end

A Possible Design





Basic PassManager

CommandLine 2.0 API

Add in transform passes

Setup the source and sink gather pass and basic sensitive leak pass

Add .bc output writer pass

Run ‘em!

```
...
cl::opt<std::string> InputBitcodeFile(cl::Positional, cl::desc("<input.bc>"),
  cl::Required);
cl::opt<std::string> OutputBitcodeFile(cl::Positional, cl::desc("<output.bc>"),
  cl::Required);
cl::opt<bool> NaiveSDL("naive-sensitive-data-leak",
  cl::desc("Perform Naive Sensitive Data Leak Analysis"), cl::init(false));
...
int
main(int argc, char **argv)
{
    std::error_code ec;
    legacy::PassManager passManager;
    std::unique_ptr<Module> irModule;
    ModulePass *modPass;
    raw_fd_ostream *outputStream;

    cl::ParseCommandLineOptions(argc, argv);

    std::cout << "<C> Reading input bitcode file: " << InputBitcodeFile << "\n";
    irModule = parseIRFile(InputBitcodeFile, err,
      *unwrap(LLVMGetGlobalContext()));
    std::cout << "<C> Adding function externalizer pass.\n";
    FunctionExternalizer *fe = new FunctionExternalizer();
    fe->setFunctionListFilePath("conf/fexternalizer.txt");
    passManager.add(fe);
    passManager.add(createPromoteMemoryToRegisterPass());
    ...
    if (NaiveSDL) {
        std::cout << "<C> Adding naive sensitive data leak pass.\n";
        TargetCallSitesPass *pt = new TargetCallSitesPass();
        pt->setConfig(TargetCallSitesPass::SourceCall,
          "conf/sensitivesource.cfg");
        pt->setConfig(TargetCallSitesPass::SinkCall,
          "conf/sensitivesink.cfg");
        passManager.add(pt);
        NaiveSensitiveDataLeak *n = new NaiveSensitiveDataLeak();
        passManager.add(n);
    }
    ...
    outputStream = new raw_fd_ostream(OutputBitcodeFile, ec, sys::fs::F_None);
    passManager.add(createBitcodeWriterPass(*outputStream, false, true));
    /* Actually run the passes added on this module */
    passManager.run(*irModule.get());
    outputStream->close();
```

Function Externalizer

```
FunctionExternalizer::runOnModule(Module &M)
{
  errs() << "Running function externalizer pass.\n";
  std::ifstream fileHandle(this->_functionListFile);
  std::string fnName;
  // each line is a function name to externalize. XXX 0 checking :-P
  while (std::getline(fileHandle, fnName)) {
    // skip comment line.
    if (fnName.find("#", 0) == 0) {
      continue;
    }
    // Does the function exist within this module?
    Function *f = M.getFunction(fnName);
    if (f == NULL) {
      continue;
    }
    // Definition is already outside of this module.
    if (f->isDeclaration()) {
      continue;
    }
    // Remove the body (definition) of the function. Leave declaration.
    errs() << "Deleting body of function: " << f->getName().str() << "\n";
    f->deleteBody();
}
```

```
TargetCallSitesPass::parseConfig(std::string configFilePath, TargetCallType tct,
....
    for (auto memIt = mems.begin(); memIt != mems.end(); ++memIt) {
        // Does the function we'd like to check in this Module?
        std::string fnName = *memIt;
        Function *fp = M->getFunction(fnName);
...
        // Check to see if we could be this function based on arg count
        int argIdx = dict[fnName].asInt();

        // Target is a void return :-/ No dice.
        Type *rt = fp->getReturnType();
        if (argcIdx == -1 && rt->isVoidTy()) continue;
        if (argIdx != -1 && \
          (fp->arg_size() == 0 || fp->arg_size() <= (unsigned)argIdx)) continue;

        /* If no User's, then no call/invoke instruction. */
        if (fp->user_empty() == true) continue;

        /* Ok, so we have name, argument, function, and a non-empty user list */
        for (auto userIt = fp->user_begin(); userIt != fp->user_end(); ++userIt) {
            User *targUser = *userIt;
            // Just handle call/invoke's for now
            if (!isa<CallInst>(targUser) && !isa<InvokeInst>(targUser)) continue;
            Instruction *targInst = cast<Instruction>(targUser);
            std::unique_ptr<TargetCallSite> tcs(new TargetCallSite(targInst, argIdx));
            targetCallMap[tct].push_back(std::move(tcs));
...
bool
TargetCallSitesPass::runOnModule(Module &M)
{
    ...
        parseConfig(p, t, &M);
    ...
    return false;
}
```

Is function in this module?

Check function return type & argument counts

skip unused functions

Is a use case a *call* instruction

Utilize TargetCallSitesPass

```
struct NaiveSensitiveDataLeak : public ModulePass {
    static char ID;
    typedef std::pair<Function *, unsigned> FuncArg;
    typedef std::map<std::string, FuncArg> FuncArgMap;

    NaiveSensitiveDataLeak() : ModulePass(ID) { }
    virtual bool runOnModule(Module &);
    virtual void getAnalysisUsage(AnalysisUsage &) const;
private:
    void parseAndCheckConfig(FuncArgMap *, bool);
    void printResult(TargetCallSite *srcSite, TargetCallSite *snkSite);

};
```

Declare the new pass & define getAnalysisUsage

```
void
NaiveSensitiveDataLeak::getAnalysisUsage(AnalysisUsage &AU) const
{
    AU.addRequired<TargetCallSitesPass>();
}
```

Inform PassManager this pass relies on TargetCallSitesPass

Utilize TargetCallSitesPass

```
bool
NaiveSensitiveDataLeak::runOnModule(Module &M)
{
    errs() << "Running naive sensitive data leak pass\n";
    TargetCallSitesPass &p = getAnalysis<TargetCallSitesPass>();

    if (p.src_empty()) {
        return false;
    }
    if (p.snk_empty()) {
        return false;
    }
...
```

Get reference to the pass that ran
&
make use of it’s API for results

Check if sensitive Values are arguments to leaky functions

For each sink, get ptr to leaked Value

For each source we have, compare leaked Value with sourced Value

```
for (auto snkIt = p.snk_begin(); snkIt != p.snk_end(); ++snkIt) {
    TargetCallSite *snkSite = &*snkIt->get();
    Value *leakData = snkSite->getTarget();
    auto srcIt = p.src_end();
    --srcIt;
    bool brk_back = false;
    for (; brk_back == false; --srcIt) {
        if (srcIt == p.src_begin()) {
            brk_back = true;
        }
        TargetCallSite *srcSite = &*srcIt->get();
        Value *originalSourceData = srcSite->getTarget();
        Value *sourceData = originalSourceData;
        if (isa<CallInst>(leakData) || isa<InvokeInst>(leakData)) {
            if (leakData == sourceData) {
                printResult(srcSite, snkSite);
                break;
            }
        }
    }
}
```

```
[awr@anathema comminute] build/bin/Comminute -naive-sensitive-data-leak tests/NSDL001.bc foo.bc
<C> Reading input bitcode file: tests/NSDL001.bc
<C> Adding function externalizer pass.
<C> Adding mem2reg pass.
<C> Adding constant propagation passes.
<C> Adding naive sensitive data leak pass.
<C> Adding bitcode writer pass
<C> Running passes
Running function externalizer pass.
Running target call sites pass.
Running naive sensitive data leak pass
  ! sensitive data leak
     leaks_passwd calls getaddrinfo where arg idx #0 is tainted sensitive. file: NSDL001.c line: 28
        source: leaks_passwd calls getpass at line: 20 of file: NSDL001.c
<C> Finished...
```

Ok… that *was* quite the contrived sensitive data leak :P

What about Phi nodes?

```
.eaks_passwd(unsigned lookup)
:
    char *p, *a2l = "www.cw-complex.com";
    struct addrinfo hints, *result;
    if (lookup) {
        p = getpass("enter passwd: ");
    } else {
        p = a2l;
    }
    memset(&hints, 0, sizeof(struct addrinfo));
    hints.ai_family = AF_UNSPEC;
    hints.ai_socktype = SOCK_DGRAM;
    hints.ai_flags = 0;
    hints.ai_protocol = 0;
    (void)getaddrinfo(p, "http", &hints, &result);  /* which path did p take? */
```

Slightly different C

```
define void @leaks_passwd(i32) #0 {
  %2 = alloca %struct.addrinfo, align 8
  %3 = alloca %struct.addrinfo*, align 8
  %4 = icmp ne i32 %0, 0
  br i1 %4, label %5, label %7

; <label>:5:                                      ; preds = %1
  %6 = call i8* @getpass(i8* getelementptr inbounds ([15 x i8], [15 x i8]* @.str.1, i32 0, i32 0))
  br label %8

; <label>:7:                                      ; preds = %1
  br label %8

; <label>:8:                                      ; preds = %7, %5
  %.0 = phi i8* [ %6, %5 ], [ getelementptr inbounds ([19 x i8], [19 x i8]* @.str, i32 0, i32 0), %7 ]
  %9 = bitcast %struct.addrinfo* %2 to i8*
  call void @llvm.memset.p0i8.i64(i8* %9, i8 0, i64 48, i32 8, i1 false)
  %10 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %2, i32 0, i32 1
  store i32 0, i32* %10, align 4
  %11 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %2, i32 0, i32 2
  store i32 2, i32* %11, align 8
  %12 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %2, i32 0, i32 0
  store i32 0, i32* %12, align 8
  %13 = getelementptr inbounds %struct.addrinfo, %struct.addrinfo* %2, i32 0, i32 3
  store i32 0, i32* %13, align 4
  %14 = call i32 @getaddrinfo(i8* %.0, i8* getelementptr inbounds ([5 x i8], [5 x i8]* @.str.2, i32 0,
```

IR output (w/ mem2reg)

Obviously fails! Values don’t match.

```
[awr@anathema comminute] build/bin/Comminute -naive-sensitive-data-leak tests/NSDL003.bc foo.bc
<C> Reading input bitcode file: tests/NSDL003.bc
<C> Adding function externalizer pass.
<C> Adding mem2reg pass.
<C> Adding constant propagation passes.
<C> Adding naive sensitive data leak pass.
<C> Adding bitcode writer pass
<C> Running passes
Running function externalizer pass.
Running target call sites pass.
Running naive sensitive data leak pass
<C> Finished...
```

Axe Method

- Goal: remove use of PHINode value “hurting” our analysis
- Axe:

```
cl::opt<int> ChoosePhiValuePass("choose-phi-value",
  cl::desc("Choose value to use from PhiNode (defaults to first)"),
  cl::init(-1));
```

  - Choose incoming branch for ALL PHINodes
  - Replace all those uses with chosen branch Value
  - Attempts to remove basic blocks for no longer used branches
- *Awfulness*: no real reasoning going on, just elimination of edges and nodes of a graph :(

```
for (auto &f : M) {
  std::vector<std::pair<PHINode *, Value *>> replaceList;
  for (auto ii = inst_begin(f); ii != inst_end(f); ++ii) {
      Instruction *in = &*ii;
      if (PHINode *pn = dyn_cast<PHINode>(in)) {
        unsigned usedEdge = edgeIndex;
        if (pn->getNumIncomingValues() <= edgeIndex) {
          errs() << "Not enough incoming values...using 0\n";
          usedEdge = 0;
        }
        Value *x = pn->removeIncomingValue(usedEdge, false);
        replaceList.push_back(std::make_pair(pn, x));
      }
  }
  if (replaceList.empty() == false) {
    rv = true;
  }
  for (auto pc : replaceList) {
    /* Replace all uses of the PHINode with the selected Value */
    pc.first->replaceAllUsesWith(pc.second);
    while (pc.first->getNumIncomingValues() > 0) {
      Value *d = pc.first->removeIncomingValue((unsigned)0, false);
      /* Each instruction resides in a BasicBlock */
      assert(isa<Instruction>(d) == true);
      Instruction *vi = cast<Instruction>(d);
      BasicBlock *bb = vi->getParent();
      if (bb->user_empty()) {
        bb->eraseFromParent();
        continue;
      }
      /* Attempt to remove users of BasicBlock so we can axe it */
      attemptUserReduction(bb);
      if (bb->user_empty()) {
        bb->eraseFromParent();
        continue;
      }
    }
    assert(pc.first->users_empty());
    pc.first->eraseFromParent();
  }
```

Select incoming branch to use

Replace all PHINode uses with branch's Value

Attempt to remove stale Basic Blocks (See code)

```
[awr@anathema comminute] build/bin/Comminute -naive-sensitive-data-leak -choose-phi-value 0 tests/NSDL003.bc foo.bc
<C> Reading input bitcode file: tests/NSDL003.bc
<C> Adding function externalizer pass.
<C> Adding mem2reg pass.
<C> Adding constant propagation passes.
<C> Adding phi value selector pass
<C> Using edge index: 0
<C> Adding naive sensitive data leak pass.
<C> Adding bitcode writer pass
<C> Running passes
Running function externalizer pass.
Running choose phi value pass.
Running target call sites pass.
Running naive sensitive data leak pass
  ! sensitive data leak
     leaks_passwd calls getaddrinfo where arg idx #0 is tainted sensitive. file: NSDL003.c line: 30
        source: leaks_passwd calls getpass at line: 21 of file: NSDL003.c
<C> Finished...
```

```
[awr@anathema comminute] build/bin/Comminute -naive-sensitive-data-leak -choose-phi-value 1 tests/NSDL003.bc foo.bc
<C> Reading input bitcode file: tests/NSDL003.bc
<C> Adding function externalizer pass.
<C> Adding mem2reg pass.
<C> Adding constant propagation passes.
<C> Adding phi value selector pass
<C> Using edge index: 1
<C> Adding naive sensitive data leak pass.
<C> Adding bitcode writer pass
<C> Running passes
Running function externalizer pass.
Running choose phi value pass.
Running target call sites pass.
Running naive sensitive data leak pass
<C> Finished...
```

Much more to worry about

- Code provided relies on simplicity, but that's a joke.
- Want to reason about:
  - execution order / control flow (or make assumptions)
  - pointers (i.e. aliasing)
  - inter-procedural analysis
- **T**hat is where a lot of research is being done…
  - see SVF project and how they handle value flow tracking
  - See ValueFlow API
  - See Andersen's Alias Analysis for pointer reasoning

Small Example: IntFlip

- Find function calls w/ at least 1 argument is an integer
- RT replace int used w/ different value with probability 1-*p*
- Use *arc4random*() with a given *mean* value…
- Either return random value or bit flip of original

Lift a constant to variable

Instruction visitor to reach all Call and Invoke

is argument a ConstantInt?

Get space for it
Save constant value to it
Replace argument to fn call

```
visitCallSite(CallSite callSite)
{
  unsigned numArgOps = callSite.getNumArgOperands();
  unsigned argIdx;

  for (argIdx = 0; argIdx < numArgOps; argIdx++) {
    Value *va = callSite.getArgOperand(argIdx);

    if (ConstantInt *con = dyn_cast<ConstantInt>(va)) {
      unsigned nBits = con->getBitWidth();
      AllocaInst *localized__alloc = new AllocaInst(
        IntegerType::get(callSite.getParent()->getContext(), nBits),    // type to allocate
        "__intflip_localized",  // give the slot a label
        callSite.getInstruction());     // Insert before call instruction
      StoreInst *localized__store = new StoreInst(
        con,    // value to store
        localized__alloc,  // where to store it
        callSite.getInstruction());     // Insert before call instruction
      LoadInst *localized__load = new LoadInst(
        localized__alloc,       // pointer to load from
        (const char *)"__intflip_loaded",       // label the slot
        callSite.getInstruction());     // Insert before call instruction
      /* replace the constant in the function call */
      callSite.setArgument(argIdx, localized__load);
      new_vars++;
      modified = true;
    }
  }
}
```

** This is from the *intflip* code

Add Existing Function (libc)

- Lookup|insert declaration:

```
Constant *lookupRand = M.getOrInsertFunction("arc4random", Type::getInt32Ty(ctx), NULL);
```

Find function named “arc4random” with return type int32 and no arguments

** This is from the *intflip* code

C representation

```
int8_t
__bitflip_randomizer_i8__(int8_t inArg0)
{
  unsigned rv = arc4random();
  if (rv <= (unsigned)2^31) {
    rv = 1 << (rv % 8);
    return inArg0 ^ rv;
  }
  return inArg0;
}
```

IR version

```
define i8 @__bitflip_randomizer_i8__(i8 %intToFlip, i32 %meanValue) {
entry:
  %__bf_rand_ = call i32 @arc4random()
  %__bf_lessthan_ = icmp ule i32 %__bf_rand_, %meanValue
  br i1 %__bf_lessthan_, label %bf_it, label %return

bf_it:                                            ; preds = %entry
  %__bf_bitflip_ = urem i32 %__bf_rand_, 8
  %__bf_cast_randrem_ = trunc i32 %__bf_bitflip_ to i8
  %__bf_shifted_bit_ = shl i8 1, %__bf_cast_randrem_
  %__bf_xord_retval_ = xor i8 %intToFlip, %__bf_shifted_bit_
  ret i8 %__bf_xord_retval_

return:                                           ; preds = %entry
  ret i8 %intToFlip
}
```

LLVM generating the IR

```
/* declare i8 __bitflip_randomizer_i8__(i8, i32) */
std::string int8_rand = "__bitflip_randomizer_i8__";
Constant *cTmp = M.getOrInsertFunction(int8_rand,
    Type::getInt8Ty(ctx),                // return
    Type::getInt8Ty(ctx),                // arg 0
    Type::getInt32Ty(ctx),               // arg 1
    NULL);
Function *bf_i8 = cast<Function>(cTmp);
bf_i8->setCallingConv(CallingConv::C);
....
BasicBlock *blkEntry = BasicBlock::Create(ctx, "entry", bf_i8);
BasicBlock *blkBitFlipIt = BasicBlock::Create(ctx, "bf_it", bf_i8);
BasicBlock *blkReturn = BasicBlock::Create(ctx, "return", bf_i8);
/*
 * entry:
 *  %__bf_rand_ = call i32 @arc4random()
 *  %__bf_lessthan_ = icmp ule i32 %__bf_rand_, %meanValue
 *  br i1 %__bf_lessthan_, label %bf_it, label %return
 */
IRBuilder<> builder(blkEntry);
Value *callArc4Random = builder.CreateCall(fnRand, None, "__bf_rand_", nullptr);
Value *lessThan = builder.CreateICmpULE(callArc4Random, &inArg1, "__bf_lessthan_");
Value *branchBitFlip = builder.CreateCondBr(lessThan, blkBitFlipIt, blkReturn);
/*
 * bf_it:                                        ; preds = %entry
 *  %__bf_bitflip_ = urem i32 %__bf_rand_, 8
 *  %__bf_cast_randrem_ = trunc i32 %__bf_bitflip_ to i8
 *  %__bf_shifted_bit_ = shl i8 1, %__bf_cast_randrem_
 *  %__bf_xord_retval_ = xor i8 %intToFlip, %__bf_shifted_bit_
 *  ret i8 %__bf_xord_retval_
 */
builder.SetInsertPoint(blkBitFlipIt);
Value *randModulus = ConstantInt::get(IntegerType::get(ctx, 32), nBits, false);
Value *randRemainder = builder.CreateURem(callArc4Random, randModulus,
    "__bf_bitflip_");
Value *defaultBit = ConstantInt::get(IntegerType::get(ctx, nBits), 1, false);
Value *castRandRem = builder.CreateZExtOrTrunc(randRemainder,
    Type::getInt8Ty(ctx), "__bf_cast_randrem_");
Value *shiftedBit = builder.CreateShl(defaultBit, castRandRem,
    "__bf_shifted_bit_");
Value *xordReturnVal = builder.CreateXor(&inArg0, shiftedBit, "__bf_xord_retval_");
builder.CreateRet(xordReturnVal);
/*
 * return:                                       ; preds = %entry
 *  ret i8 %intToFlip
 */
builder.SetInsertPoint(blkReturn);
builder.CreateRet(&inArg0);
```

Declare function

Add some basic blocks

Use IRBuilder to add to blkEntry

re-use same IRBuilder

** This is from the *intflip* code

Say we have code:

```
char
bf8(char in)
{
        return in;
}
```

```
static void *
thd_bf8(void *a)
{
        for (unsigned i = 0; i < MAXITER; i++)
                printf("thd_bf8: %d\n", bf8(0));
        return a;
}
```

Inject call to new function

```
for (inst_iterator I = inst_begin(f), E = inst_end(f); I != E; ++I) {
    if (isa<CallInst>(&*I) || isa<InvokeInst>(&*I)) {
        CallSite cs(&*I);
        Function *called = cs.getCalledFunction();
        if (!called->hasName()) {
            continue;   // XXX Currently require functions to have names
        }
       ....
        unsigned numArgOps = cs.getNumArgOperands();
        for (unsigned ii = 0; ii < numArgOps; ii++) {
            Value *va = cs.getArgOperand(ii);
            Type *ta = va->getType();
            /*
             * If not a 8, 16, 32, or 64 bit integer, we skip it.
             */
            if (TypeValueSupport::isReplaceable(ta, va) == false) {
                continue;
            }
          ....
            unsigned nBits = ta->getIntegerBitWidth();
            Function *insertedRndFn = M.getFunction(rndFnName);
            assert(insertedRndFn != NULL);
            ConstantInt *mn = ConstantInt::get(M.getContext(), APInt(32, mFc.mean, false));
            /*
             * Insert call to randomizer with input integer and a mean value.
             * It will be inserted before the CallInst.
             */
            CallInst *callNewFunc = CallInst::Create(insertedRndFn,
                { va, mn }, // Arguments are the integer to maybe flip and the mean value
                "__rnd_replicant_",
                cs.getInstruction());   // insert our call to the rnd fn before the targeted call instruction
            cs.setArgument(ii, callNewFunc);

    }
```

** This is from the *intflip* code

Performs following transform

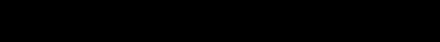
```
; <label>:7:                                     ; preds = %4
  %8 = call signext i8 @bf8(i8 signext 0)
  %9 = sext i8 %8 to i32
```



```
; <label>:7:                                     ; preds = %4
  %__intflip_localized = alloca i8
  store i8 0, i8* %__intflip_localized
  %__intflip_loaded = load i8, i8* %__intflip_localized
  %__rnd_replicant_ = call i8 @__bitflip_randomizer_i8__(i8 %__intflip_loaded, i32 100000000)
  %8 = call signext i8 @bf8(i8 signext %__rnd_replicant_)
  %9 = sext i8 %8 to i32
```

And running…

```
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd bf8: 0
```



```
thd_bf8: 32
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 0
thd_bf8: 16
thd_bf8: 0
```

Concluding Remarks

- Re-usability and modularity in developing security tools is essential
- Common platform makes research and sharing much easier
- LLVM provides robust APIs for doing both research & development
- Many (important?) groups are using LLVM…

Now, please go do great research! 🤓

Some references

1. The LLVM Compiler Infrastructure, http://www.llvm.org
2. Lattner, “LLVM: An Infrastructure for Multi-Stage Optimization”, http://llvm.org/pubs/2002-12-LattnerMSThesis.html
3. “Writing an LLVM Pass”, http://llvm.org/docs/WritingAnLLVMPass.html
4. CommandLine 2.0 Library, http://llvm.org/docs/CommandLine.html
5. LLVM Language Reference, http://llvm.org/docs/LangRef.html
6. http://llvm.org/docs/CommandGuide/
7. http://llvm.org/docs/doxygen/html/index.html

Please see the projects github link for more references. Effectively all the comments related to sec r&d projects using llvm are based on those sources and reading code.