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Machine-Code Analysis and Transformation at GrammaTech

Alexey Loginov

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GrammaTech, Inc.
531 Esty Street
Ithaca, NY 14850
Tel. 607-273-7340
E-mail: alexey@grammatech.com

Why Analyze Binaries?

- Necessity: Source code unavailable, e.g., libraries, COTS
- Convenience: Even if available, often infeasible to configure source build to match platform or release of interest
- Breadth of application:
  - Works for applications written in any compiled language(s)
  - But needs approach to multiple Instruction Set Architectures
- Fidelity: may actually be better than source-code analysis
  - **WYSINWYX**: What You See Is Not What You eXecute
  - Binaries reveal platform-specific choices of compiler
  - Binary analysis can use real libraries, not hand-written models

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Why Analyze Binaries?

- Fidelity example 1
  - An optimizing compiler can introduce a dependable covert channel in the binary that is not apparent in the source code

```
_f:
        push ebp
        mov ebp, esp
        push ecx        ; allocates 4 bytes in frame
        . . .           ; "Uninitialized" local gets value of ecx
```

- Fidelity example 2
  - An optimizing compiler can undo your security precautions

```
void f() {
        char password[N];
        . . .
        memset(password, '\0', len);
        return;
}
```


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Model-Extraction Challenges

- Subtasks for intermediate representation (IR) recovery
  - Distinguishing between code and data
  - Distinguishing between scalar and symbolic values (addresses)
  - Identifying dynamic libraries that may be loaded
  - Identifying procedure boundaries
  - Identifying variables, their sizes, and their types
  - Identifying parameters, their sizes, and their types
  - Resolving indirect jumps
  - Resolving indirect calls
  - Building inter-procedural control-flow graph (CFG)
  - Deriving useful reverse-engineering meta-data, e.g., effects on heap, file system, etc.

Disassembly Challenges Boiled Down

- Basic questions
  - What code is executed?
  - What data is accessed?
- It's about boundaries
  - Between code and data
  - Between procedures
  - Between separate pieces of data
- … and symbols
  - Is a given value a scalar or an address?
- … in the presence of indirection
  - Extensive indirection in control flow
  - Extensive indirection in data accesses

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Indirection Examples in Control Flow

- Library/function lookup by name
  - `LoadLibrary, GetProcAddress`
- Library-function calls via thunks, import tables
  - `call [_imp__MessageBoxA@16]`
  - … with register-indirect calls as repeated-call optimizations
    - `mov eax, [_imp__MessageBoxA@16]`
    - `… call eax … call eax …`
- Virtual-function calls via v-tables
- Switch statements via jump tables

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Indirection Examples in Data Accesses

- Formal/local accesses via stack/frame pointers
  - `mov eax,[esp+8];  mov eax,[ebp-4]`
  - Explicit offsets may or may not indicate a data boundary
    - `mov eax,[ebp-4]`: could be the last element of an array
- Strength-reduced computations of offsets into aggregates
  - `lea eax, [eax + eax*2]`
  - `lea ebx, [ebx + eax*4 + 0x12345678]`
- Globals referenced by their address
  - `mov eax, [0x12345678]`
  - Non-zero-based accesses make it difficult to determine layout

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Indirection Challenges

- Understanding indirection requires
  - Substantial numeric analysis
    - Value ranges, strides, linear relations
  - Symbol propagation
  - String analysis

Outline

- Analyzing binaries: why and why is it hard?
- Foundations of sound analyses
- Program transformation
- Heuristic analyses
- Stack-object delineation
- A comprehensive approach to security

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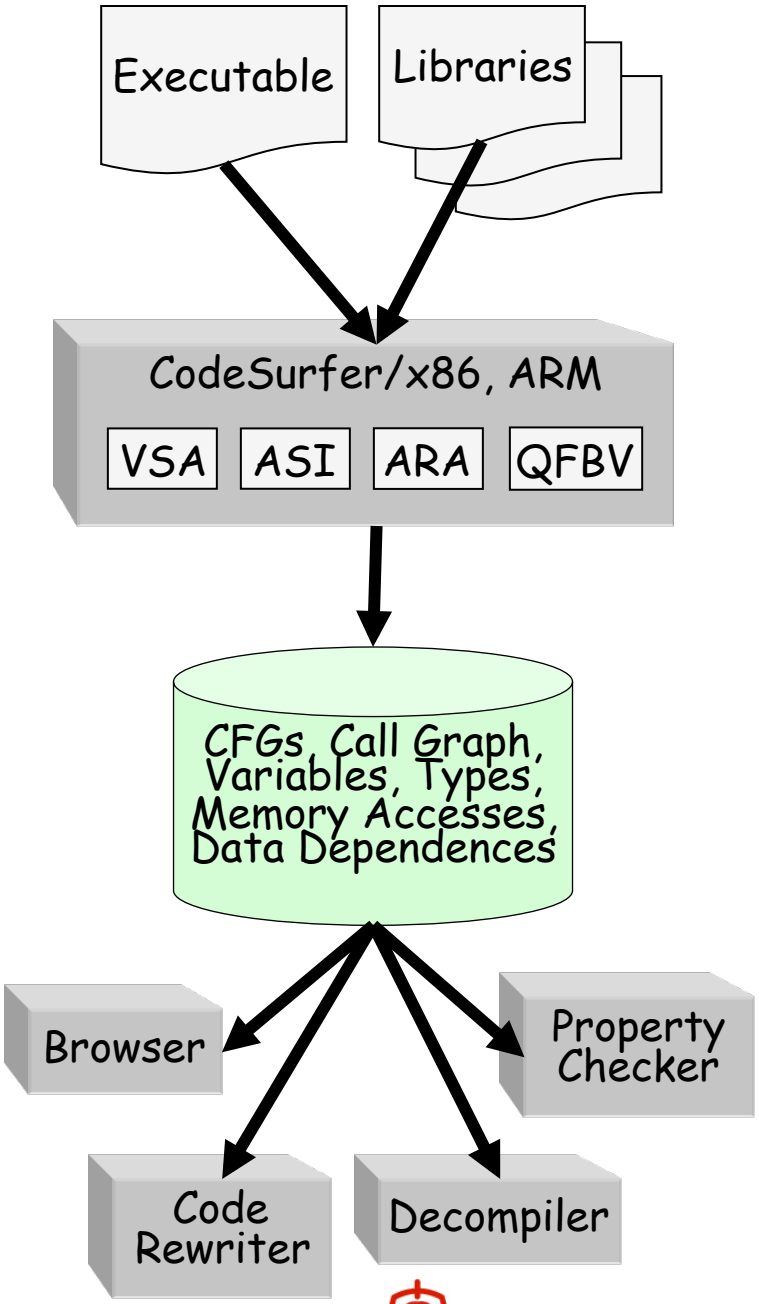
Core Analyses

- VSA: Value-Set Analysis
  - Compute possible contents of variables
    - Both integer and pointer values
  - Compute information about memory accesses
    - Memory locations read, written
- ASI: Aggregate-Structure Identification
  - Identify variables and types
- ARA: Affine-Relation Analysis
  - Identify induction variables
  - Identify other key linear relations
    - E.g., between stack and frame pointers
- QFBV: Quantifier-Free Bit-Vectors
  - Logical representation of instruction semantics
    - Amenable to heuristic and formal reasoning



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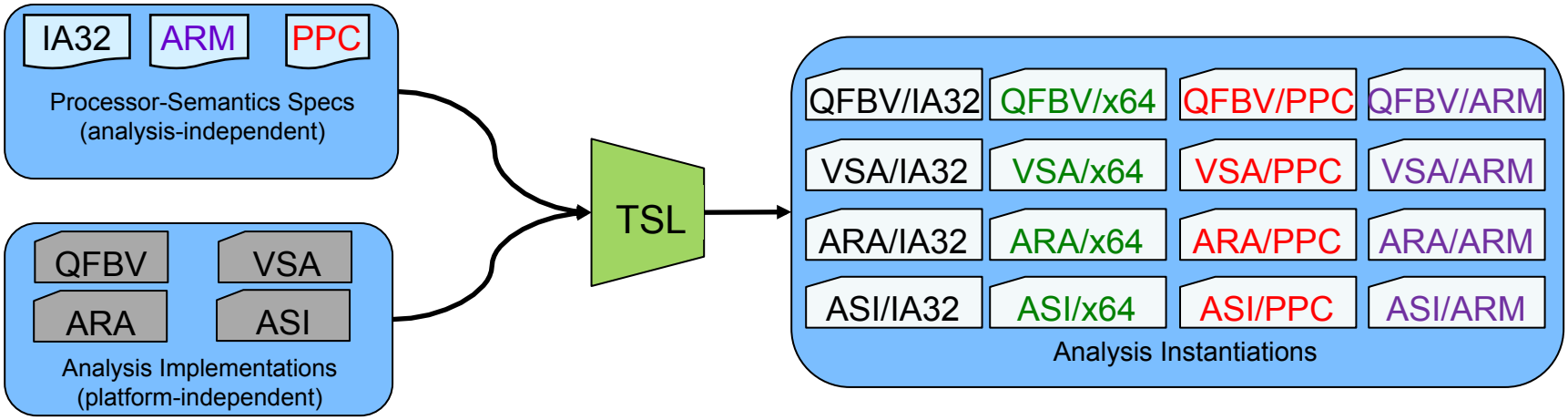
TSL/ISAL: Automatic Analysis Retargeting

- Separate processor semantics specs from analysis implementations
- Automatically generate platform-specific analysis instantiations
- Benefits:
  - Independence of semantics and analyses
    - Validation of each ISA semantics is separate from static analyses
    - Validation of each static analysis is separate from ISA definitions
  - Consistency. All analyses for given ISA driven off of same definition
  - Completeness. Full analysis generated for all instructions.



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TSL: Formal ISA Semantics

- Specifies concrete operational semantics of an ISA
  - Uses small set of platform-independent operations

```
state interpInstr(instruction I, state S)
{
 with(I) (
  MOV(dspOp, srcOp):
   let srcVal = interpOp(S, srcOp) in (
     updateState(S, dspOp, srcVal)
   ),
  ADD(dstOp, srcOp):
   let dstVal = interpOp(S, dstOp);
       srcVal = interpOp(S, srcOp);
       sum = dstVal + srcVal;
   in ( updateState(S, dstOp, sum) )
 )
};
```

```
INT32 interpOp(state S, operand srcOp)
{
 with(S) ( State(mem, regs, flags):
   with(srcOp) (
    DirectReg(r): regs(r),
    Indirect(base, disp):
      let base_v = regs(base);
          addr = base_v + disp;
      in ( mem(addr) ),
    Immediate(i): i
  )
 )
};
```

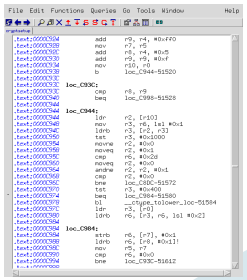
Validation Infrastructure

Validate model of processor state

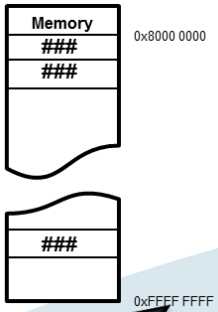
Validate abstract domains and solvers

var_20 ϵ [5, 30]
ptr → g
r13 ≤ r11 - #06c

Validate ICFG construction



Register	Value
r0	###
r1	###
r2	###
r3	###
r4	###
r5	###
r6	###
r7	###
r8	###
r9	###
r10	###
r11	###
r12	###
r13	###
r14	###
r15	###
PSR	###



compare

Abstract Analyses

compare

Concrete Semantics

compare

Disassembly

compare

ISAL spec (decoder)

Validate instruction decoding

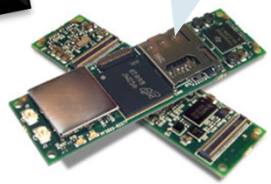
```
stmdb  r13!, {r4,r5,r6,r7,r8,r9,r10,r11,lr}
sub    r13, r13, #0x490
sub    r13, r13, #0xc
str    r0, [r13, #0x38]
ldr    r0, [r13, #0x4c0]
mov    r9, r2
ldr    r0, [r0, #0x8]
ldr    r2, [r13, #0x4c0]
cmp    r0, #0xc
ldr    r2, [r2, #0x28]
str    r0, [r13, #0x34]
```

QEMU trace

```
0xf67d85ac:  e24dd084    sub  sp, sp, #132    ; 0x84
0xf67d85b0:  e08fc00c    add  ip, pc, ip
0xf67d85b4:  e24b5024    sub  r5, fp, #36     ; 0x24
0xf67d85b8:  e59f6dd4    ldr  r6, [pc, #3540] ; 0xf67d9394
0xf67d85bc:  e3a0a000    mov  sl, #0  ; 0x0
0xf67d85c0:  e59ce000    ldr  lr, [ip]
0xf67d85c4:  e1a04000    mov  r4, r0
0xf67d85c8:  e50b5068    str  r5, [fp, #-104]
0xf67d85cc:  e08f6006    add  r6, pc, r6
0xf67d85d0:  e59f5dc0    ldr  r5, [pc, #3520] ; 0xf67d9398
0xf67d85d4:  e15e000a    cmp  lr, sl
0xf67d85d8:  e59fcdbc    ldr  ip, [pc, #3516] ; 0xf67d939c
0xf67d85dc:  e2867ff3    add  r7, r6, #972    ; 0x3cc
0xf67d85e0:  e08f5005    add  r5, pc, r5
0xf67d85e4:  e50b105c    str  r1, [fp, #-92]
0xf67d85e8:  e08fc00c    add  ip, pc, ip
0xf67d85ec:  e59f1dac    ldr  r1, [pc, #3500] ; 0xf67d93a0
0xf67d85f0:  e5950000    ldr  r0, [r5]
0xf67d85f4:  13a0e009    movne        lr, #9  ; 0x9
0xf67d85f8:  01a0e00a    moveq        lr, sl
0xf67d85fc:  e087700e    add  r7, r7, lr
0xf67d8600:  e58c7124    str  r7, [ip, #292]
0xf67d8604:  e08f1001    add  r1, pc, r1
```

objdump

```
0101010010101010010
1010101000101010010
1010010101111101010
0101000100110010100
0010100100010101010
1010101010000001011
0010100001010000101
1010101010111111010
0101010101110111110
000100101
```



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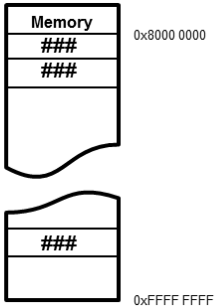
r2	###
r3	###
r4	###
r5	###
r6	###
r7	###
r8	###
r9	###
r10	###
r11	###
r12	###
r13	###
r14	###
r15	###
PSR	###



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Outline

- Analyzing binaries: why and why is it hard?
- Foundations of sound analyses
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- A comprehensive approach to security

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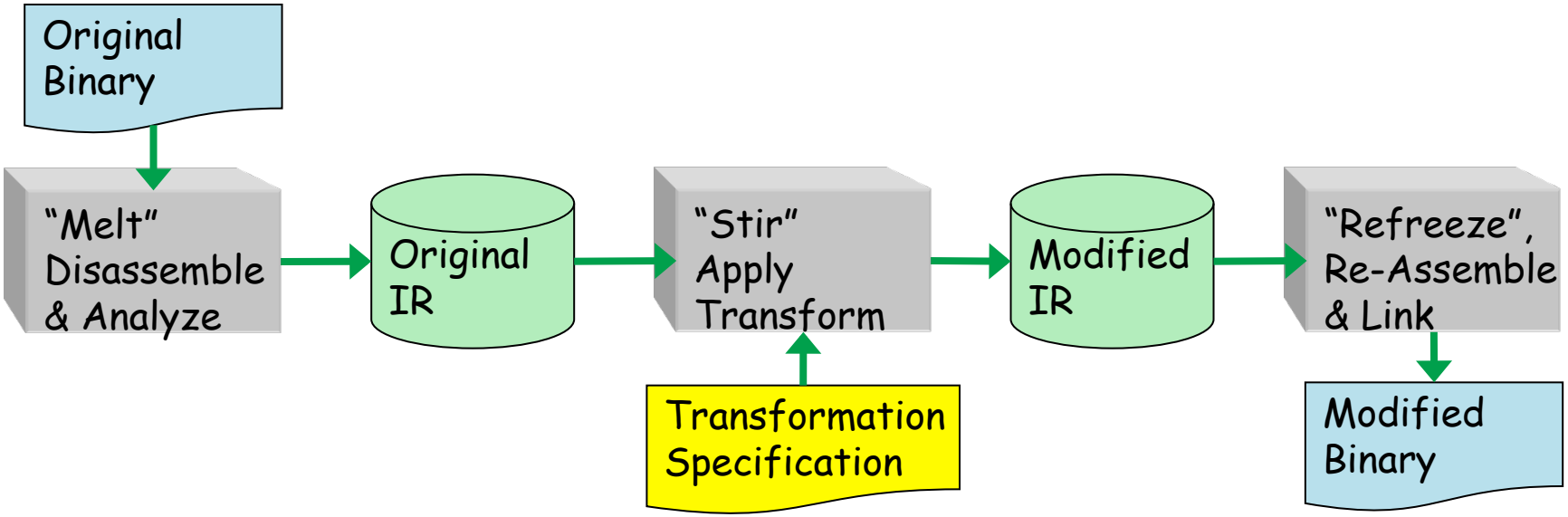
Melt-Stir-and-Refreeze Rewriting

Whole program rewriting

- CodeSurfer
  - *Melt*: Recover high-fidelity Intermediate Representation (IR)
  - *Stir*: Transform IR based on scripts written in C, C++, Scheme, Python, etc.
  - *Refreeze*: Emit assembly
- Applications
  - Performance, patching, security (obfuscation, diversification, IP protection)



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Sample Transformations

- "Null" transform
  - Not identity: reassembly will result in new placement of data, code
- Converting dynamic linking to static linking
- Abstraction-layer removal (inlining+simplification)
- Simple specialization/partial evaluation
- Dead code removal
- SLX: stack-layout transformation

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Case Study: GNU coreutils

- 104 Linux executables
  - Sizes range: 24K-115K
  - Package includes substantial test coverage of each executable
  - Initial melt phase: IDA Pro
    - Stir ("Null" transform) and refreeze break tests for every executable
  - Current melt phase: IDA Pro + GT improvements to IR
    - Stir (many transforms) and refreeze preserve all tested functionality

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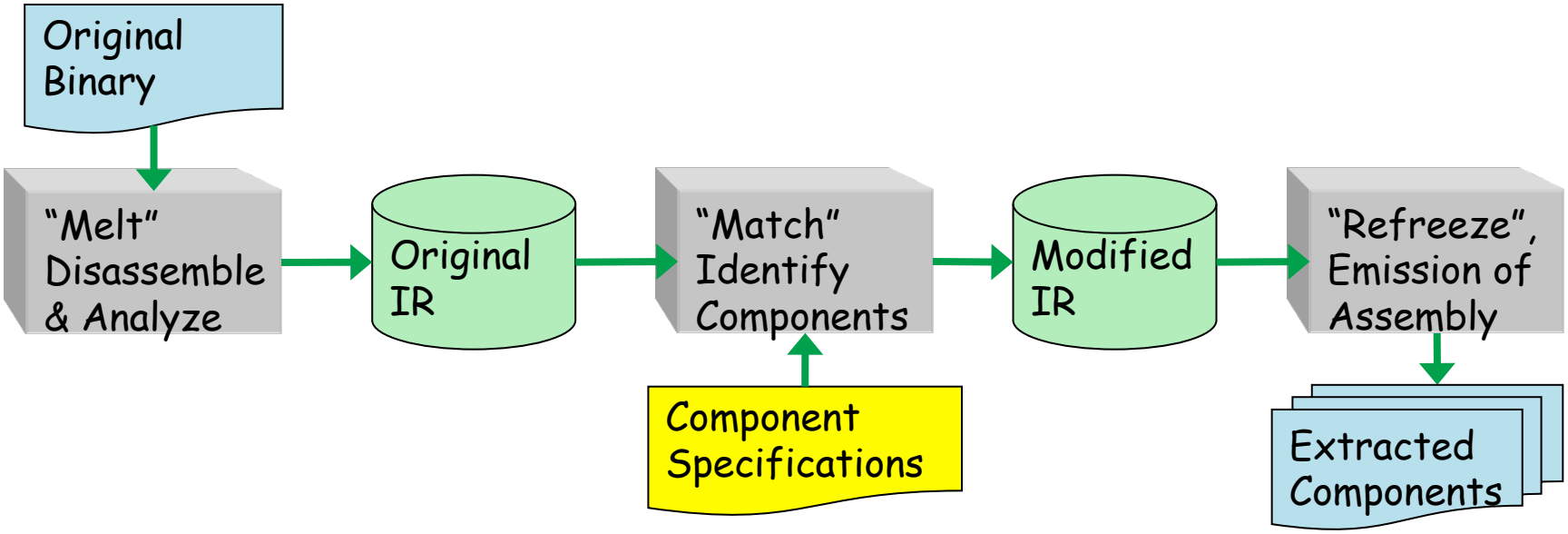
Melt-Match-and-Refreeze Rewriting

Component Extraction

- CodeSurfer
  - *Melt*: Recover high-fidelity Intermediate Representation (IR)
  - *Match*: Pattern match in IR for components of interest
  - *Refreeze*: Emit assembly and high-level metadata for located components
- Applications
  - Reuse of components in legacy software



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CodeSonar/C,C++

- A source-code analyzer that finds serious flaws in software
  - Language Misuse
  - Library Misuse
  - Enforcement of domain-specific rules
- Sample checks
  - Buffer Overrun
  - Null-Pointer Dereference
  - Divide by Zero
  - Uninitialized Variable
  - Free Null Pointer
  - Unreachable Code
  - Dangerous Cast
  - Missing Return Statement
  - Return Pointer to Local
  - Format String Vulnerability
  - Free Non-Heap Variable
  - Use After Free/Close
  - Double Free/Close
  - Memory/Resource Leak
  - Mismatched Array New/Delete
  - Invalid Parameter
  - Unchecked Return Code
  - Race Condition

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Buffer Overrun at lexpgn.c:2205

Jump to warning location ↓

No properties have been set. | edit properties

warning details...

Show Events | Options

return_append_str *(/bal0/magagnosc/src/trunk-swyx.opti/codesonar-tests/regression/swyx/precision/gnuchess-5.07-src.temp/gnuchess-5.07/src/lexpgn.c)*

```
2197  char *return_append_str(char *dest, const char *s) {
2198  /* Append text s to dest, and return new result. */
2199          char *newloc;
2200          size_t newlen;
2201          /* This doesn't have buffer overflow vulnerabilities, because
2202             we always allocate for enough space before appending. */
2203          if (!dest) {
2204                  newloc = (char *) malloc(strlen(s))+1;
2205                  strcpy(newloc, s);
```

Buffer Overrun

This code writes past the end of the buffer pointed to by `newloc`.

- `newloc` evaluates to `malloc(strlen(s)) + 1` from **lexpgn.c:2204**.
- `strcpy()` writes to the byte at an offset that is the length of the string pointed to by `s`, plus 1 from the beginning of the buffer pointed to by `newloc`.
  - The offset exceeds the capacity.
  - The length of the string pointed to by `s`, plus 1 is no less than `1`. See related event 8.
  - The capacity of the buffer pointed to by `newloc`, in bytes, is the length of the string pointed to by `s`, which is bounded below by `0`. See related events 6 and 9.
- The overrun occurs in heap memory.

The issue can occur if the highlighted code executes.

See related events 6, 8, and 9.

Show: All events | Only primary events

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CODESONAR Search code in this analysis for Search | Advanced Search

Home › gnuchess-5.07-lin-src › gnuchess-5.07-lin-src analysis 1 › Warning 1271265.26666235 Text | XML | ReML | Visible Code: all

Buffer Overrun at lexpgn.c:2205

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Show Events | Options

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2205                  strcpy(newloc, s);
```


```
newloc = (char *) malloc(strlen(s))+1;
strcpy(newloc, s);
```


See related events 6 and 9.

- The overrun occurs in heap memory.

The issue can occur if the highlighted code executes.

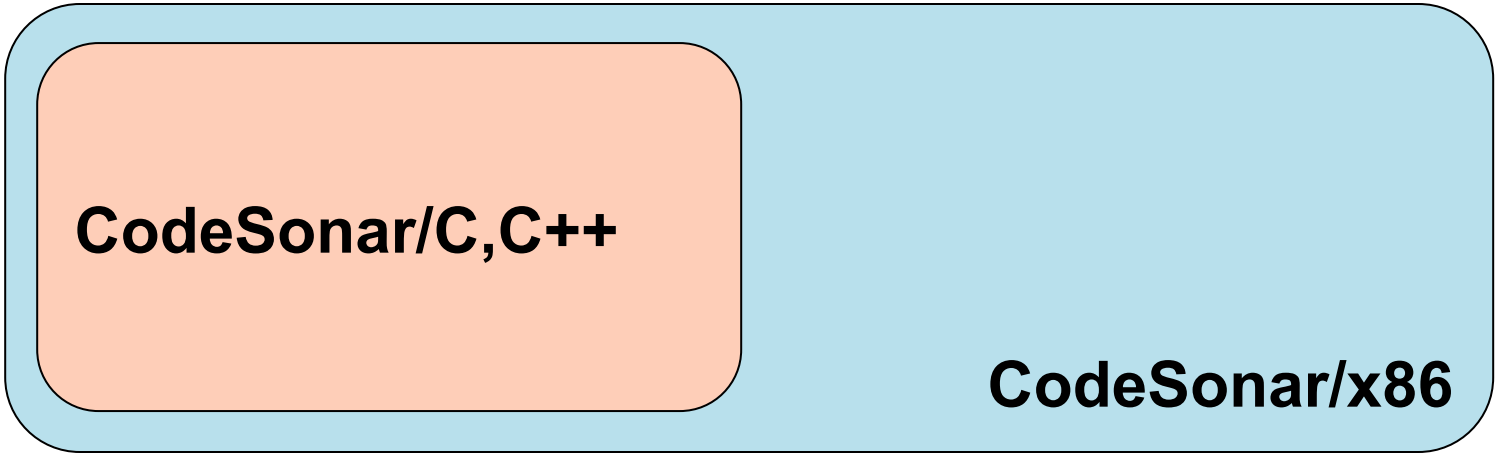
See related events 6, 8, and 9.

Show: All events | Only primary events

CodeSonar for Binaries

Tool input is source and/or binary

- Tool for binary code is an extension of source-code tool
- Input is a combination of source and binary



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CODESONAR

Search code in this analysis for Search

Advanced Search

Home › gnuchess-5.07-lin-swyx › gnuchess-5.07-lin-swyx analysis 5 › Warning

133933.487983

Text | XML | ReML | Visible Code: all

Buffer Overrun at gnuchess.lst:39513

Jump to warning location ↓

No properties have been set. | edit properties

warning details...

Categories: LANG.MEM.BO CWE:120 CWE:788

```
39502   _text:08065AEC          dd 0x2c746D
39503
39504   _text:08065AF0
39505   _text:08065AF0  loc_8065AF0:
39506   _text:08065AF0          mov     dword [esp],edi
39507   _text:08065AF3          call    __thunk_.strlen
39508   _text:08065AF8          mov     dword [esp],eax
39509   _text:08065AFB          call    __thunk_.malloc
```

Event 15: `malloc()` returns the address of a new object.
- This points to the buffer that will be overrun later.

▲ ▼ hide

```
39510   _text:08065B00          mov     dword [esp+4],edi
39511   _text:08065B04          lea     ebx, [eax+1]
39512   _text:08065B07          mov     dword [esp],ebx
39513   _text:08065B0A          call    __thunk_.strcpy
```

Buffer Overrun

This code writes past the end of the buffer pointed to by `strcpy:parameter_1`.

- `strcpy:parameter_1` evaluates to `malloc() + 1` from **gnuchess.lst:39509**.
- `strcpy()` writes to the byte at an offset that is the length of the string pointed to by `strcpy:parameter_2`, plus 1 from the beginning of the buffer pointed to by `strcpy:parameter_1`.
  - The offset exceeds the capacity.
  - The length of the string pointed to by `strcpy:parameter_2`, plus 1 evaluates to the length of the string pointed to by `s`, plus 1, which is bounded below by `1`. See related event 23.
  - The capacity of the buffer pointed to by `strcpy:parameter_1`, in bytes, is the length of the string pointed to by `s`, which is bounded below by `0`. See related events 16 and 22.
- The overrun occurs in heap memory.

The issue can occur if the highlighted code executes.

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CODESONAR Search code in this analysis for Search

```
39506   _text:08065AF0          mov     dword [esp],edi
39507   _text:08065AF3          call    __thunk_.strlen
39508   _text:08065AF8          mov     dword [esp],eax
39509   _text:08065AFB          call    __thunk_.malloc
```

Event 15: `malloc()` returns the address of a new object.

- This points to the buffer that will be overrun later.

▲ ▼ hide

```
39510   _text:08065B00          mov     dword [esp+4],edi
39511   _text:08065B04          lea     ebx, [eax+1]
```

Event 19: `ebx` is set to `eax + 1`, which evaluates to `malloc() + 1` fr

```
39512   _text:08065B07          mov     dword [esp],ebx
39513   _text:08065B0A          call    __thunk_.strcpy
```

```
newloc = (char *) malloc(strlen(s))+1;
strcpy(newloc, s);
```

- The offset exceeds the capacity.
- The length of the string pointed to by `strcpy:parameter_2`, plus 1 evaluates to the length of the string pointed to by `s`, plus 1, which is bounded below by `1`. See related event 23.
- The capacity of the buffer pointed to by `strcpy:parameter_1`, in bytes, is the length of the string pointed to by `s`, which is bounded below by `0`. See related events 16 and 22.

- The overrun occurs in heap memory.

The issue can occur if the highlighted code executes.

Heuristics for Scalability

- Need for scalability/linear cost requires modular analysis
- Examples of helper analyses supporting modular analysis
  - Save-restore pairs and truly-live registers
    - For type inference, parameter identification, …
  - Affine-relations analysis between esp, ebp, etc.
    - For analyzing frame delta (stack height) in the presence of
      - Indirect calls (with varying calling conventions)
      - Stack allocation (alloca)
  - Local value-set analysis
    - For resolving repeated calls via the import table (cl optimization)

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Library Models for Precision

- Most analyses rely on models of library functions
  - CodeSurfer models for dependences
  - CodeSonar models for symbolic transformations
  - ARA models for effect on stack pointer
  - …
- Challenges
  - Writing them and keeping them in sync
  - Identifying calls to library functions!
    - Dynamic linking (easy): import-table information
    - Static linking (harder): IDA Pro's FLIRT (pattern-matching)
    - Static linking with inlining (hardest)
      - Limited pattern-matching (concentrate on string- and buffer-manipulation)
      - Instruction reordering complicates things

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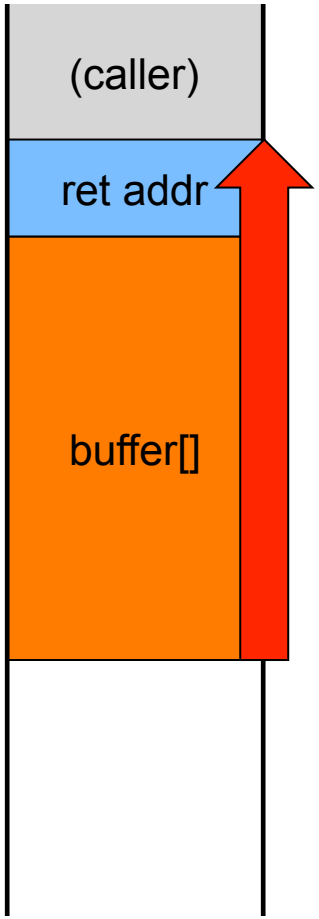
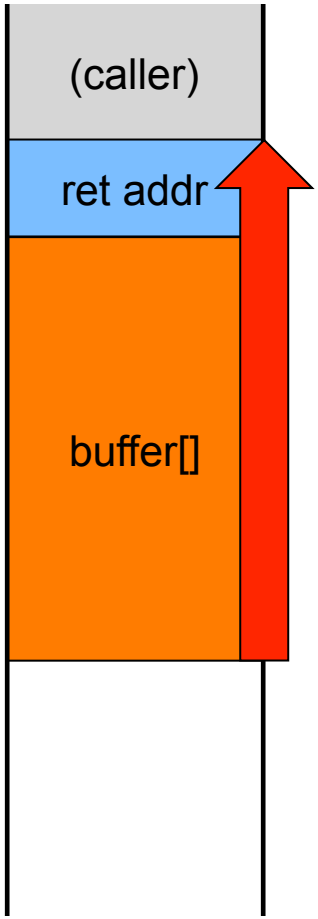
A Classic Buffer Overflow



gets(buffer);

A Classic Buffer Overflow



- Can detect in CodeSonar
  - Return-address location is known
- Can protect using:
  - Shadow stacks
  - Padding
  - Activation-record canary / guard
  - Taint propagation

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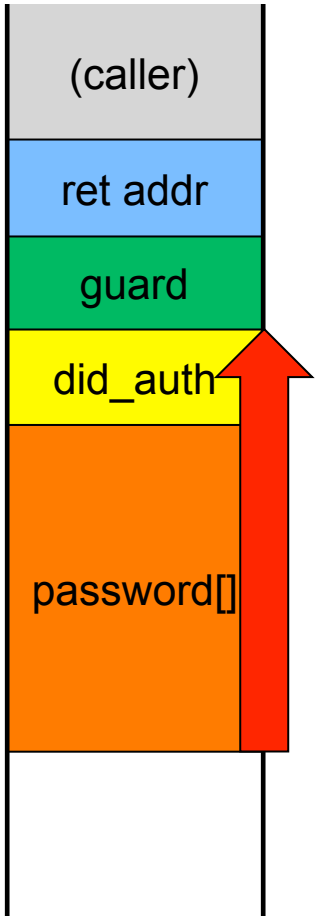
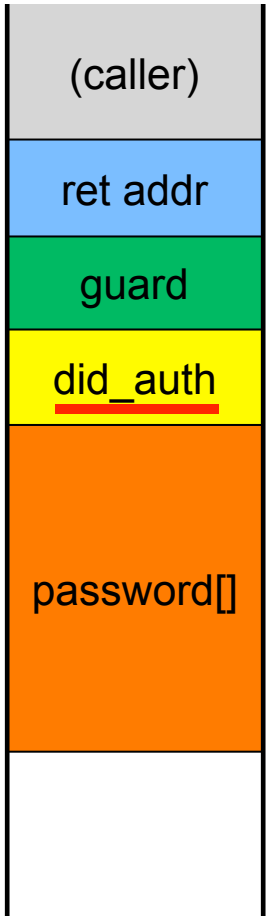
What About Intra-frame Overruns?




```
bool did_auth = false;
char password[12];

gets(password);
if (strcmp(password, “hunter2”) == 0)
    did_auth = true;
…
if (did_auth)
    do_something_important();
```

What About Intra-frame Overruns?



- Non-control data attacks:
  - Do not smash stack
  - Overwrite important program data

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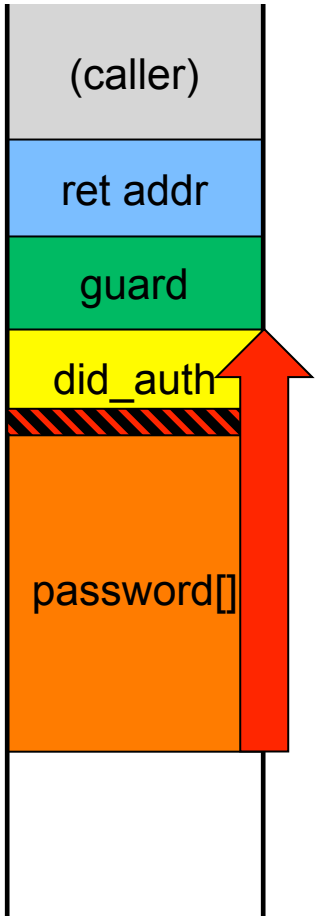
What About Intra-frame Overruns?



- Non-control data attacks:
  - Do not smash stack
  - Overwrite important program data
- Need to infer stack-object boundaries

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CodeSonar Stack-Buffer-Overrun Detection

- Two modes for stack-buffer overruns:
  - Stack-smashing only (false negatives)
  - Intra-frame overruns (false positives, if using all stack-offset bounds)

    We want this without this!

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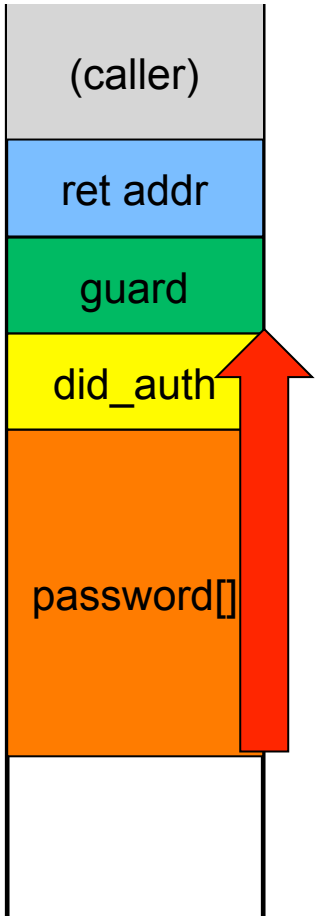
Accuracy is Important!



- Too conservative (missed “true” boundaries)
  - Some objects are left unprotected
  - Weakened defenses
  - Static analysis (CodeSonar) misses problems

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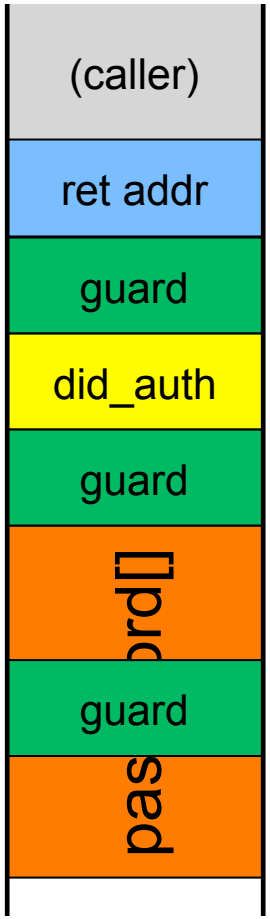
Accuracy is Important!



- Too aggressive (found “false” boundaries)
  - Transformations (e.g., SLX) may break program
  - Static analysis (CodeSonar) will report false positives

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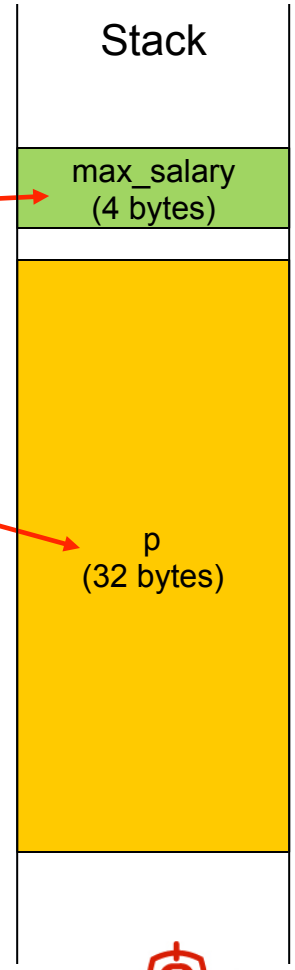
SOD: Source Code

- Object boundaries are directly specified
  - Also applies to binaries with debug info

```
int get_max_salary(int age)
{
    int max_salary = 0;
    struct Person p;

    while (read_person_data(&p))
    {
        if (p.age == age) {
            if (p.salary >= max_salary) {
                max_salary = p.salary;
            }
        }
    }

    return max_salary;
}
```



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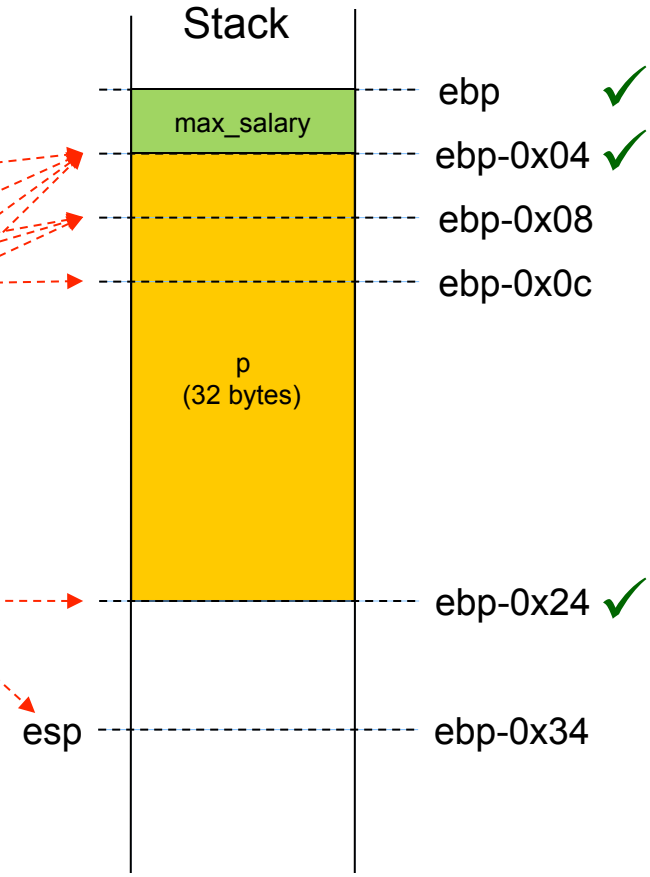
SOD: Stripped Binary

- No variable declarations
  - Local variables are numeric offsets into the procedure frame

```
080483be <get_max_salary>:
 80483be:  push   %ebp
 80483bf:  mov    %esp,%ebp
 80483c1:  sub    $0x34,%esp
 80483c4:  movl   $0x0,-0x4(%ebp)
 80483cb:  jmp    80483e3
 80483cd:  mov    -0xc(%ebp),%eax
 80483d0:  cmp    0x8(%ebp),%eax
 80483d3:  jne    80483e3
 80483d5:  mov    -0x8(%ebp),%eax
 80483d8:  cmp    -0x4(%ebp),%eax
 80483db:  jl     80483e3
 80483dd:  mov    -0x8(%ebp),%eax
 80483e0:  mov    %eax,-0x4(%ebp)
 80483e3:  lea    -0x24(%ebp),%eax
 80483e6:  mov    %eax,(%esp)
 80483e9:  call   80483b4 <read_person_data>
 80483ee:  test   %eax,%eax
 80483f0:  jne    80483cd
 80483f2:  mov    -0x4(%ebp),%eax
 80483f5:  leave
 80483f6:  ret
```



Existing Techniques

- Reverse-Engineering Heuristics
  - Stack offsets appearing in binary (as in IDA Pro)
    - Generally too aggressive (finds spurious boundaries)
- Existing sound static analyses
  - DIVINE, ASI, VSA
  - Too conservative, not sufficiently scalable
  - Only work for memory-safe programs
    - Will use unsafe memory accesses to infer object bounds
- Dynamic analysis of memory-access patterns
  - Howard, Rewards, Laika
  - Require test suites:
    - That provide good coverage
    - That do not violate memory safety

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Existing Techniques

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Sound analyses are not appropriate?

- Dynamic analysis [illegible] memory-access patterns
  - Howard, Rewards, Laika
  - Require test suites:
    - That provide good coverage
    - That do not violate memory safety

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Different Notions of Soundness

- Sound transformations
  - Preserve all behaviors of program
    - But we want to preserve only memory-safe behaviors
      - Heuristic in nature
  - Must detect a subset of buffer boundaries
- Sound analysis
  - Report all potential problems
  - Must detect a superset of buffer boundaries

Parameter Offset Analysis (POA)

- Observation:
  - Functions often take objects by pointer or reference
  - Field accesses become `*(param + C)` where C is a *syntactic constant*

```
int get_max_salary(int age)
{
    int max_salary = 0;
    struct Person p;

    while (read_person_data(&p))
    {
        if (p.age == age) {
            if (p.salary >= max_salary) {
                max_salary = p.salary;
            }
        }
    }

    return max_salary;
}
```

```
struct Person
{
    char name[24];
    int age;
    int salary;
};

int read_person_data(struct Person * p)
{
    ...
    strncpy(p->name, ..., 24);
    p->age = ...;
    p->salary = ...;
    ...
}
```


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Parameter Offset Analysis (POA)

- At call-site: determine extent of locals passed as parameters

```
080483be <get_max_salary>:
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```

Local object at offset **ebp-0x24** has extent of **32 bytes**

param-1: { 24--31 }

```
int get_max_salary(int age)
{
    int max_salary = 0;
    struct Person p;

    while (read_person_data(&p))
    {
        if (p.age == age) {
            .salary >= max_salary) {
            ax_salary = p.salary;

            lary;
}
```


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Outline

- Analyzing binaries: why and why is it hard?
- Foundations of sound analyses
- Program transformation
- Heuristic analyses
- Stack-object delineation
- A comprehensive approach to security

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PEASOUP Vision

Collaboration with the University of Virginia, Georgia Tech, and Raytheon

Software Executable

PEASOUP Analyzer

- Recovers:
  - Structure
  - Vulnerabilities
- Generates prog. variants:
  - Repairs or confines vulnerabilities
  - Alters attack surface
- Checks correctness, strength

Hardened Executable

SOUP: Software Of Uncertain Provenance

- Not malicious, but …
- Not safe from attack!
  - Includes:
  - Doc, PDF viewers
  - Media players
  - Utilities (zip, etc.)
  - Web browsers

- Immune to many attacks
- On malicious input:
  - Corrected execution
  - Controlled exit
  - Uncontrolled exit
  - *Stops exploits!*

This material is based upon work supported by the United States Air Force under Contract No. FA8650-10-C-7025

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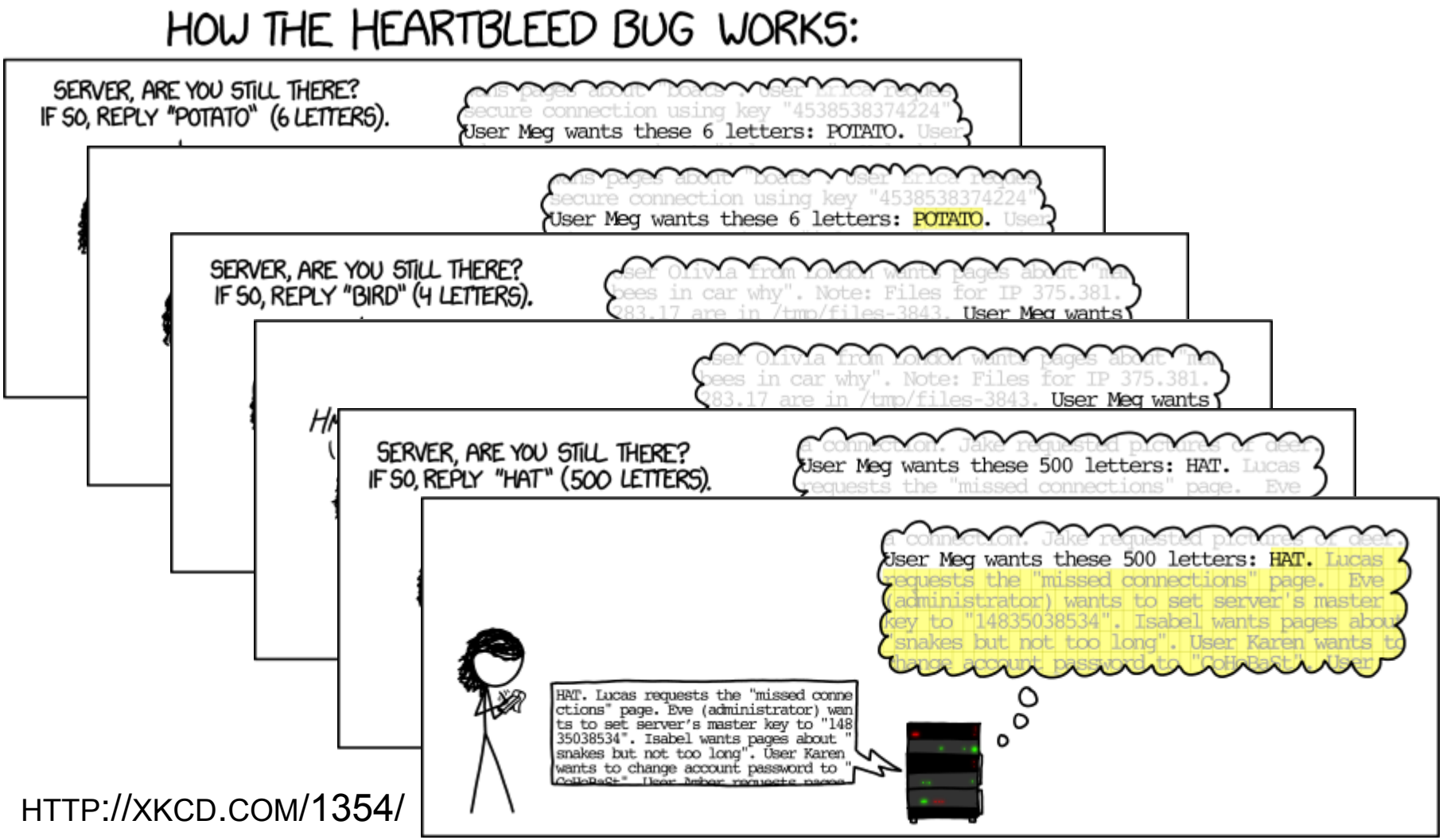
xkcd explanation of Heartbleed



HTTP://XKCD.COM/1354/

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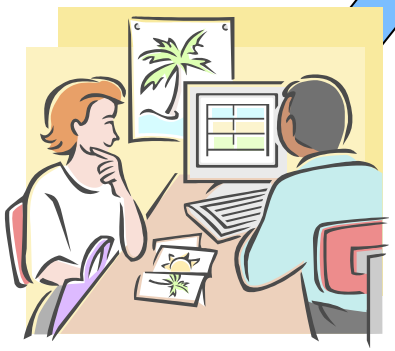
PEASOUP and Heartbleed

+ PEASOUP

(nginx server)



3. Server ~~leaks sensitive diagnoses in response~~ detects attack, sends zeros

1. Health Corp employee enters sensitive diagnoses via “secure” web client

2. Hacker repeatedly sends Heartbleed attacks

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Thank you!