CMPSC 447
Static Analysis

Trent Jaeger
Systems and Internet Infrastructure Security (SIIS) Lab
Computer Science and Engineering Department
Pennsylvania State University

Our Goal

- One option is to develop automated techniques to detect vulnerabilities before they can be exploited
  - Your program may have flaws that may lead to a vulnerabilities
  - How to find them?

Dynamic Analysis Limits

- Major advantage
  - When we produce a crash, it is a real crash
- Major limitation
  - We cannot find all vulnerabilities in a program with dynamic testing in most cases
- Why not?

Dynamic Analysis Limits

- Major advantage
  - When we produce a crash, it is a real crash
- Major limitation
  - We cannot find all vulnerabilities in a program with dynamic testing in most cases
- Why not?
  - Cannot run all possible inputs in most cases

Goal

- Can we build a technique that identifies *all* vulnerabilities?

Goal

- Can we build a technique that identifies *all* flaws?
  - Turns out that we can: static analysis
  - Over-approximate all possible executions of a program, so any flaw that can happen will be found
    - And some flaws that are not really possible (false positives)
  - But, can be effective when used carefully

Static Analysis

- Explore all possible executions of a program
  - All possible inputs
  - All possible states

A Form of Testing

- Static analysis is an alternative to dynamic testing
- Dynamic
  - Select concrete inputs
  - Obtain a sequence of states given those inputs
  - Apply many concrete inputs (i.e., run many tests)
- Static
  - Select abstract inputs with common properties
  - Obtain sets of states created by executing abstract inputs
  - One “run”

Static Analysis

- Provides an approximation of behavior
- "Run in the aggregate"
  - Rather than executing on ordinary states
  - Finite-sized descriptors representing a collection of states
- "Run in non-standard way"
  - Run in fragments
  - Stitch them together to cover all paths
- Runtime testing is inherently incomplete, but static analysis can cover all paths

Static Analysis

- Consider the following code

```
int main(int argc, char **argv) {
    char *buf1R1;
    char *buf2R1;
    char *buf2R2;
    char *buf3R2;

    buf1R1 = (char *) malloc(BUFSIZER1);
    buf2R1 = (char *) malloc(BUFSIZER1);

    free(buf2R1);

    buf2R2 = (char *) malloc(BUFSIZER2);
    buf3R2 = (char *) malloc(BUFSIZER2);

    strncpy(buf2R1, argv[1], BUFSIZER1-1);
    free(buf1R1);
    free(buf2R2);
    free(buf3R2);
}
```

Static Analysis

- Can we find a use-after-free flaw?

```
int main(int argc, char **argv) {
    char *buf1R1;
    char *buf2R1;
    char *buf2R2;
    char *buf3R2;

    buf1R1 = (char *) malloc(BUFSIZER1);
    buf2R1 = (char *) malloc(BUFSIZER1);

    free(buf2R1);

    buf2R2 = (char *) malloc(BUFSIZER2);
    buf3R2 = (char *) malloc(BUFSIZER2);

    strncpy(buf2R1, argv[1], BUFSIZER1-1);
    free(buf1R1);
    free(buf2R2);
    free(buf3R2);
}
```

Static Analysis

- Various properties of programs can be tracked
  - Control flow
  - Constants
  - Types
  - Values (sets of values)
  - Data flow
- Which ones will expose which vulnerabilities accurately (and not too many false positives) requires some finesse

Control Flow Analysis

- Compute the control flow of a program
  - I.e., possible execution paths
- To find an execution path that leads to a use-after-free for a pointer
  - That may be run by the program
    - Overapproximates executions
    - For just the part of the program of interest
  - How do we do this?

Intraprocedural CFG

- Statements
  - Nodes
  - One successor and one predecessor
- Basic Blocks
  - Multiple successors (multiple predecessors)
- Unique Enter and Exit
  - All start nodes are successors of enter
  - All return nodes are predecessors of exit

Control Flow for Example

- What is this example's control flow

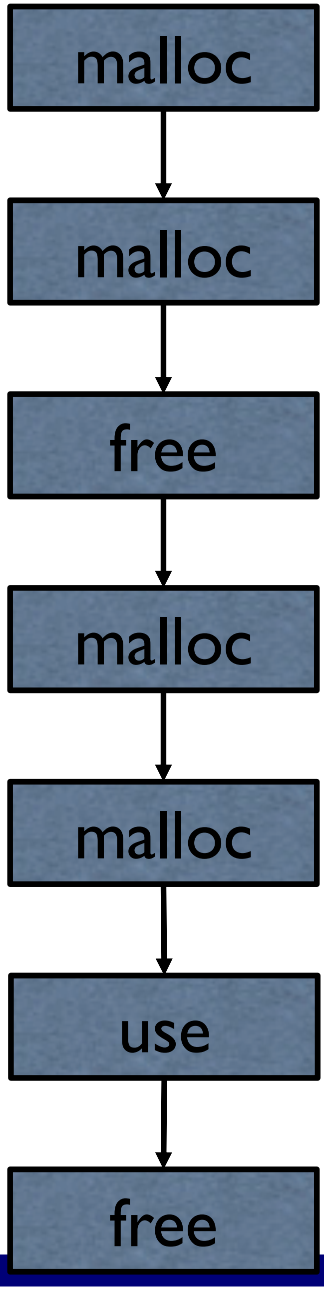
```
int main(int argc, char **argv) {
    char *buf1R1;
    char *buf2R1;
    char *buf2R2;
    char *buf3R2;

    buf1R1 = (char *) malloc(BUFSIZER1);
    buf2R1 = (char *) malloc(BUFSIZER1);

    free(buf2R1);

    buf2R2 = (char *) malloc(BUFSIZER2);
    buf3R2 = (char *) malloc(BUFSIZER2);

    strncpy(buf2R1, argv[1], BUFSIZER1-1);
    free(buf1R1);
    free(buf2R2);
    free(buf3R2);
}
```



Control Flow for Example

- Ah ha! A "use" after a "free"

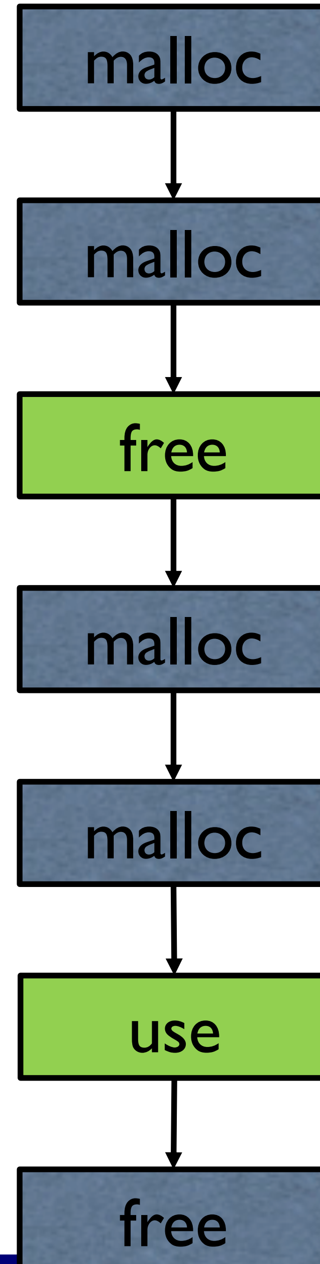
```
int main(int argc, char **argv) {
    char *buf1R1;
    char *buf2R1;
    char *buf2R2;
    char *buf3R2;

    buf1R1 = (char *) malloc(BUFSIZER1);
    buf2R1 = (char *) malloc(BUFSIZER1);

    free(buf2R1);

    buf2R2 = (char *) malloc(BUFSIZER2);
    buf3R2 = (char *) malloc(BUFSIZER2);

    strncpy(buf2R1, argv[1], BUFSIZER1-1);
    free(buf1R1);
    free(buf2R2);
    free(buf3R2);
}
```



Control Flow for Example

- Happens to refer to the same pointer

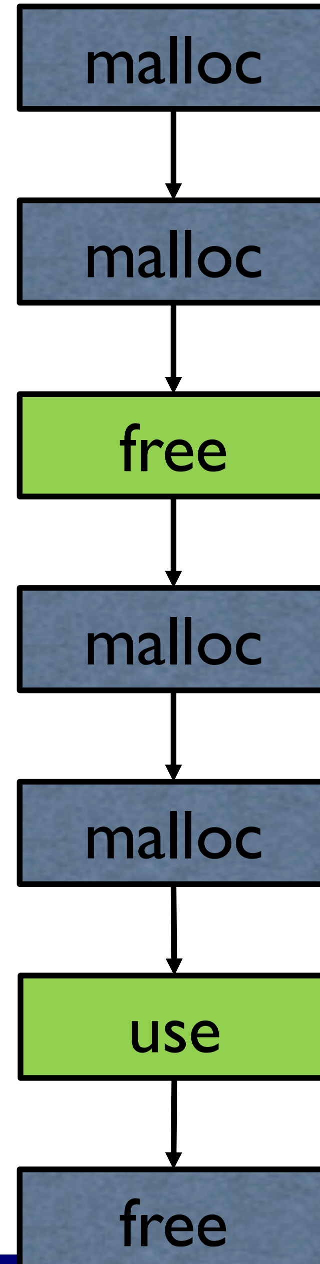
```
int main(int argc, char **argv) {
    char *buf1R1;
    char *buf2R1;
    char *buf2R2;
    char *buf3R2;

    buf1R1 = (char *) malloc(BUFSIZER1);
    buf2R1 = (char *) malloc(BUFSIZER1);

    free(buf2R1);

    buf2R2 = (char *) malloc(BUFSIZER2);
    buf3R2 = (char *) malloc(BUFSIZER2);

    strncpy(buf2R1, argv[1], BUFSIZER1-1);
    free(buf1R1);
    free(buf2R2);
    free(buf3R2);
}
```



Control Flow for Example

- Would be a false positive otherwise

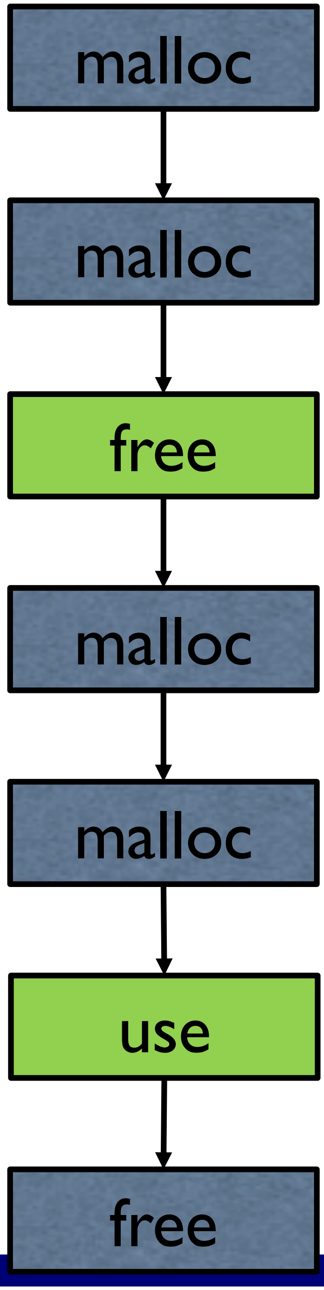
```
int main(int argc, char **argv) {
    char *buf1R1;
    char *buf2R1;
    char *buf2R2;
    char *buf3R2;

    buf1R1 = (char *) malloc(BUFSIZER1);
    buf2R1 = (char *) malloc(BUFSIZER1);

    free(buf2R1);

    buf2R2 = (char *) malloc(BUFSIZER2);
    buf3R2 = (char *) malloc(BUFSIZER2);

    strncpy(buf2R2, argv[1], BUFSIZER1-1);
    free(buf1R1);
    free(buf2R2);
    free(buf3R2);
}
```



Control Flow for Example

- Reason about possible values (concrete)

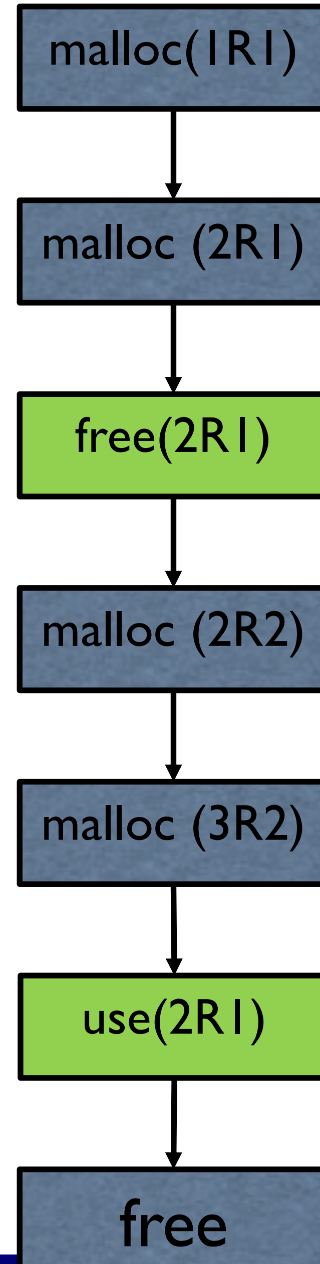
```
int main(int argc, char **argv) {
    char *buf1R1;
    char *buf2R1;
    char *buf2R2;
    char *buf3R2;

    buf1R1 = (char *) malloc(BUFSIZER1);
    buf2R1 = (char *) malloc(BUFSIZER1);

    free(buf2R1);

    buf2R2 = (char *) malloc(BUFSIZER2);
    buf3R2 = (char *) malloc(BUFSIZER2);

    strncpy(buf2R1, argv[1], BUFSIZER1-1);
    free(buf1R1);
    free(buf2R2);
    free(buf3R2);
}
```



Control Flow Analysis

- Compute Control Flow
- One function at a time – “intraprocedural”
- Program statements of interest
  - Sequences – basic blocks
  - Conditionals – transitions between basic blocks in function
  - Loops – transitions that connect to prior basic blocks
  - Calls – transition to another function
  - Return – transition that completes the function

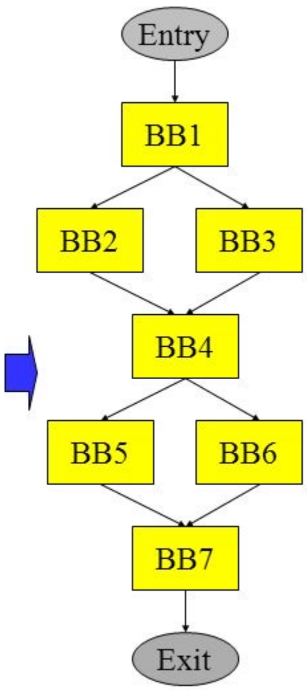
Control Flow Analysis

- Compute Intraprocedural Control Flow

From Last Time: BB and CFG

- Basic block – a sequence of consecutive operations in which flow of control enters at the beginning and leaves at the end without halt or possibility of branching except at the end
- Control Flow Graph – Directed graph, G = (V,E) where each vertex V is a basic block and there is an edge E, v1 (BB1) → v2 (BB2) if BB2 can immediately follow BB1 in some execution sequence

```
x = y+1;
if (c)
    x++;
else
    x--;;
y = z + 1;
if (a)
    y++;
else
    y—;
z++;
```



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Constant Propagation

- Substitute the values of known constants in expressions
- Propagate the values among variables assigned those constants
- Example assignments resulting from propagation to detect problems

Detect Buffer Overflow

- What are the constant values below?

```
char text[] = "Foo           Bar”;
char buffer1[4], buffer2[4];

int i, n = sizeof(text);
for(i=0;i<n;++i)
    buffer2[i] = text[i];
printf("Last char of text is: %c", text[n]);
```

Detect Buffer Overflow

- Where can they be propagated?

```c
char text[] = "Foo            Bar";
char buffer1[4], buffer2[4];

int i, n = sizeof(text);
for(i=0;i<n;++i)
    buffer2[i] = text[i];
printf("Last char of text is: %c", text[n]);
```

Detect Buffer Overflow

- Where are the memory errors?

```
char text[] = "Foo           Bar”;
char buffer1[4], buffer2[4];

int i, n = 20;
for(i=0;i<20;++i)
    buffer2[i] = text[i];
printf("Last char of text is: %c", text[20]);
```

Detect Buffer Overflow

- Where are the memory errors?

```
char text[] = "Foo            Bar";
char buffer1[4], buffer2[4];

int i, n = 20;
for(i=0;i<20;++i)
    buffer2[i] = text[i];
printf("Last char of text is: %c", text[20]);
```

Constant Propagation

- Typically, constant propagation is a start, but need more to detect an error
- For the buffer overflow we need to know that access to buffer2[4-19] and text[20] are memory errors

Abstract Interpretation

- Descriptors represent the sign of a value
  - Positive, negative, zero, unknown
- For an expression, *c = a * b*
  - If *a* has a descriptor *pos*
  - And *b* has a descriptor *neg*
- What is the descriptor for *c* after that instruction?
- How might this help?

Abstract Interpretation

- E.g., integer overflows
- Use unknown for signed ints
- And "<constant" for signed after (signed < constant)
- "Cast_unsigned" creates a positive from <constant
- Could we detect a problem here?

```
if (signed < constant)
  strlcpy(dst, src, (cast_unsigned)signed);
```

Type-based Analysis

- Maybe we want to check for certain properties about variables in our program
- Can use type information associated with variables to perform such checks

Type-based Analysis

- Maybe we want to check for certain properties about variables in our program
- Suppose we want to know if a variable's value has been "checked" – such as for input validation
- We can use type-based analysis to do that

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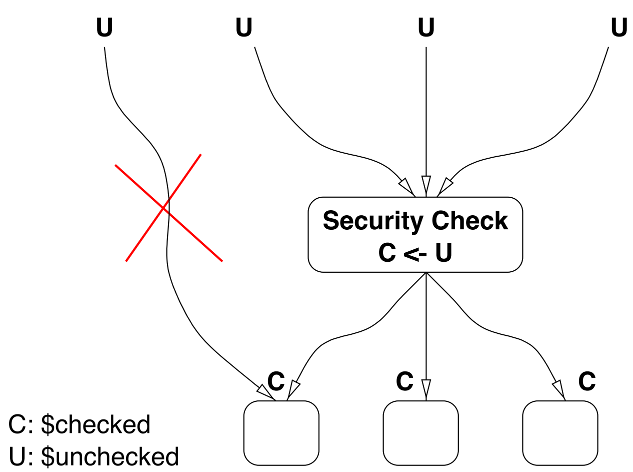
- We can use type-based analysis to do that



Type-based Analysis

- Maybe we want to check for certain properties about variables in our program
- Suppose we want to know if a variable's value has been "checked" – such as for input validation
- Using type qualifiers, can extend basic types

```
void func_a(struct file * $checked filp);

void func_b( void )
{
  struct file * $unchecked filp;
  ...
  func_a(filp);
  ...
}
```

Type-based Analysis

PENNSTATE

- Maybe we want to check for certain properties about variables in our program
- Suppose we want to know if a variable's value has been "checked" – such as for input validation
- To find missing mediation (e.g., input validation)
  - Initialize untrusted inputs to "unchecked"
  - Initialize security-sensitive operation to use "checked"
  - Identify mediation (create "checked" version)
  - Detect type error – from "unchecked" to "checked"

Type-based Analysis

- Vulnerability in the code to the right
  - Can you see it?

```
/* from fs/fcntl.c */
long sys_fcntl(unsigned int fd,
               unsigned int cmd,
               unsigned long arg)
{
  struct file * filp;
  ...
  filp = fget(fd);
  ...

  err = security_ops->file_ops
        ->fcntl(filp, cmd, arg);
  ...
  err = do_fcntl(fd, cmd, arg, filp);

  ...
}

static long
do_fcntl(unsigned int fd,
         unsigned int cmd,
         unsigned long arg,
         struct file * filp) {
  ...
  switch(cmd){
    ...
    case F_SETLK:

      err = fcntl_setlk(fd, ...);

    ...
  }
  ...
}

/* from fs/locks.c */
fcntl_getlk(fd, ...) {
  struct file * filp;
  ...

  filp = fget(fd);

  /* operate on filp */
  ...
}
```

Type-based Analysis

- Vulnerability in the code to the right
  - fd is unchecked as is filp initially in sys_fnctl
  - However, filp would be reassigned to a checked variable after security_op
- So what's the problem?

```
/* from fs/fcntl.c */
long sys_fcntl(unsigned int fd,
               unsigned int cmd,
               unsigned long arg)
{
  struct file * filp;
  ...
  filp = fget(fd);
  ...

  err = security_ops->file_ops
        ->fcntl(filp, cmd, arg);
  ...
  err = do_fcntl(fd, cmd, arg, filp);

  ...
}

static long
do_fcntl(unsigned int fd,
         unsigned int cmd,
         unsigned long arg,
         struct file * filp) {
  ...
  switch(cmd){
    ...
    case F_SETLK:

      err = fcntl_setlk(fd, ...);

    ...
  }
  ...
}

/* from fs/locks.c */
fcntl_getlk(fd, ...) {
  struct file * filp;
  ...

  filp = fget(fd);

  /* operate on filp */
  ...
}
```

Type-based Analysis

- Vulnerability in the code to the right
  - *fd* and *filp* are unchecked initially
  - *filp* is checked in sys_fnctl
  - However, *filp* is reassigned from an unchecked *fd* variable in fnctl_getlk/setlk
- *fd*, not the checked *filp* is passed to do_fcntl and to fcntl_getlk/setlk

```
/* from fs/fcntl.c */
long sys_fcntl(unsigned int fd,
               unsigned int cmd,
               unsigned long arg)
{
  struct file * filp;
  ...
  filp = fget(fd);
  ...
  err = security_ops->file_ops
        ->fcntl(filp, cmd, arg);
  ...
  err = do_fcntl(fd, cmd, arg, filp);
  ...
}

static long
do_fcntl(unsigned int fd,
         unsigned int cmd,
         unsigned long arg,
         struct file * filp) {
  ...
  switch(cmd){
    ...
    case F_SETLK:
      err = fcntl_setlk(fd, ...);
    ...
  }
  ...
}

/* from fs/locks.c */
fcntl_getlk(fd, ...) {
  struct file * filp;
  ...
  filp = fget(fd);
  /* operate on filp */
  ...
}
```

Take Away

- Static analysis evaluates all the ways that a program may execute in one pass
  - Can be "sound" (no false negatives – find all flaws)
  - But, then will likely produce some false positives
- Examined some building blocks of static analysis and how they could be used
  - Constant propagation, control flow, type analysis
- There is much more to the application of static analysis to security problems – a key for software security