IntScope : Automatically Detecting Integer Overflow Vulnerability in X86 Binary Using Symbolic Execution

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Outline

- Motivation
- Case Study
- Modeling
- Challenges & Approaches
- Implementation & Evaluation
- Related Work
- Conclusion

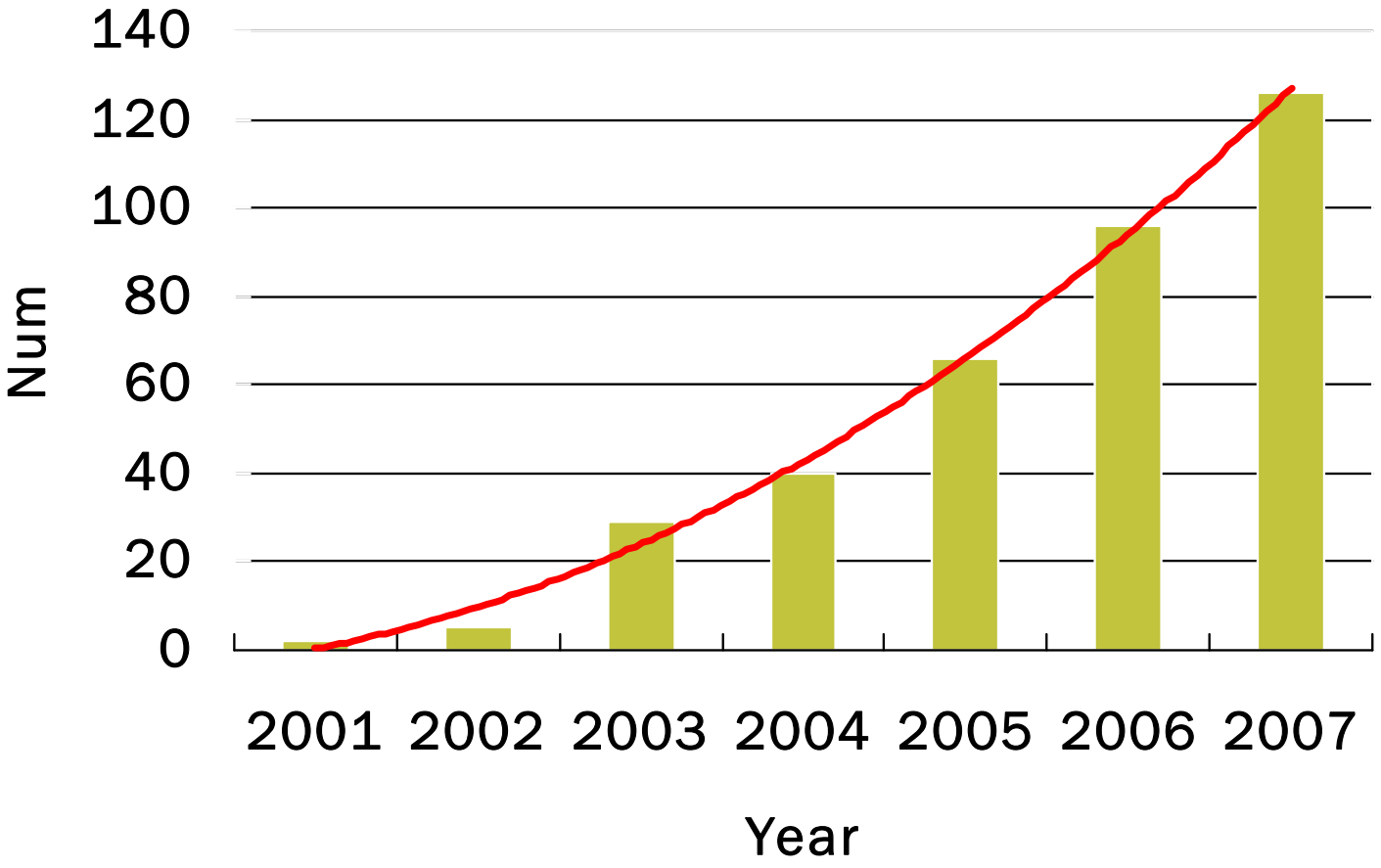
What is Integer Overflow ?

- An *integer overflow* occurs when an operation results in a value greater than the maximum one of the integral data type.

```
unsigned int a = 0xffffffff;
unsigned int b = 0x1        ;
a = a + b                   ;//now, a is 0!
```

- Integer overflow vulnerability is an underestimated threat

The # of integer overflow vulnerabilities grows rapidly



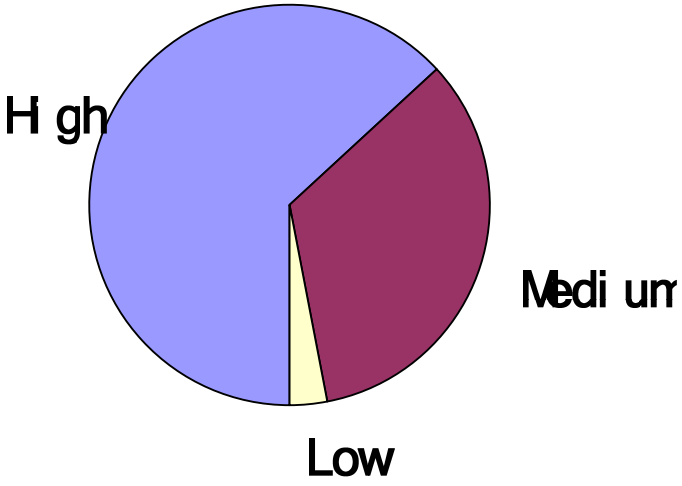
Data Source: National Vulnerability Database

Integer Overflow Vulnerabilities affected various kinds of software

- OS Kernel
  - CVE-2008-4036 (Windows XP, Server 2003, Vista)
  - CVE-2008-3276 (Linux)
  - CVE-2008-4220 (Mac OS)
  - CVE-2008-1391 (NetBSD)
  - …
- Libraries
  - CVE-2008-2316 (Python)
  - CVE-2008-5352 (JAVA)
  - …
- Applications
  - CVE-2008-0726 (Adobe Reader)
  - CVE-2008-4061 (Firefox)
  - CVE-2008-2947 (IE7)
  - CVE-2008-0120 (PowerPoint)
  - CVE-2008-1722(CUPS)
  - CVE-2008-2430(VLC)
  - CVE-2008-5238(Xine)
  - …

Most of Integer Overflow Vulnerabilities are dangerous

- According to Common Vulnerability Scoring System(CVSS), more than 60% of Integer Overflow vulnerabilities have the highest severity score.



Data Source: Common Vulnerability Scoring System

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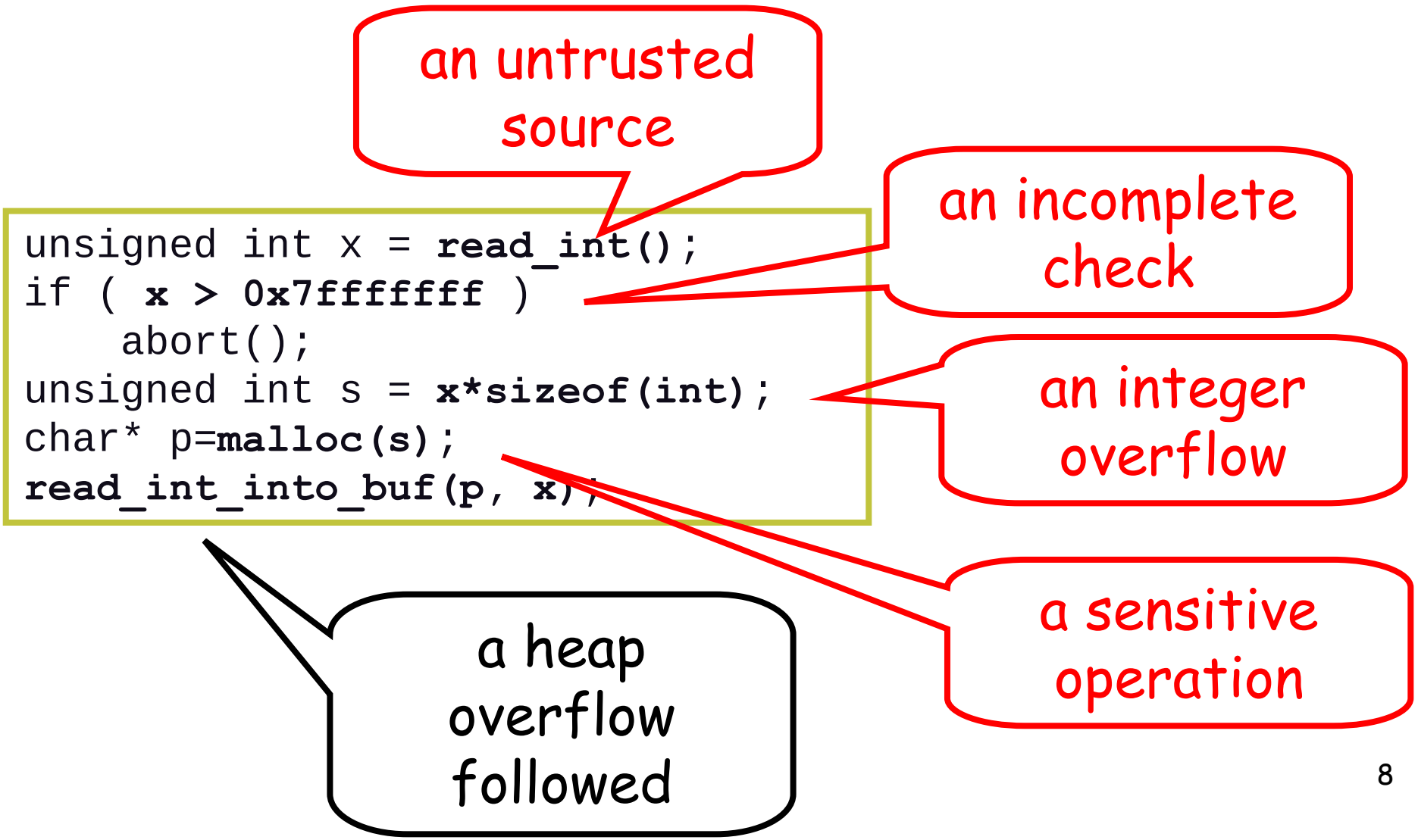
What are the common features of integer overflow vulnerabilities?



CVE-2008-5238(Xine)

```
……
if (version == 4) {
        const uint16_t sps = _X_BE_16 (this->header+44) ? : 1;
        this->w            = _X_BE_16 (this->header+42);
        this->h            = _X_BE_16 (this->header+40);
        this->cfs          = _X_BE_32 (this->header+24);
        this->frame_len = this->w * this->h;
        this->frame_size = this->frame_len * sps;
        this->frame_buffer = calloc(this->frame_size,
……
```

an untrusted source

an integer overflow

a sensitive operation

CVE-2008-1722(CUPS)

```
png_get_IHDR(pp, info, &width, &height, &bit_depth
        &interlace_type, &compression_type, &filter
{
    ……
    if (width == 0 || width > CUPS_IMAGE_MAX_WIDTH ||
        height == 0 || height > CUPS_IMAGE_MAX_HEIGHT)
    {//error
        return (1);
    }
    img->xsize = width;
    img->ysize = height;
    ……
    if (color_type == PNG_COLOR_TYPE_GRAY ||color_type ==
    PNG_COLOR_TYPE_GRAY_ALPHA)
          in = malloc(img->xsize * img->ysize);
    else
          in = malloc(img->xsize    >ysize * 3);
    ……
}
```

an untrusted source

an incomplete check

an integer overflow

a sensitive operation

CVE-2008-2430(VLC)

```
……
if( ChunkFind( p_demux, "fmt ", &i_size ) )
{
    msg_Err( p_demux, "cannot find 'fmt ' chunk"
    goto error;
}
if( i_size < sizeof( WAVEFORMATEX ) - 2 )
{
    msg_Err( p_demux, "invalid 'fmt ' chunk" );
    goto error;
}
stream_Read( p_demux->s, NULL, 8 );    /* Can

/* load waveformatex */
p_wf_ext = malloc( __EVEN( i_size ) + 2 );
……
```

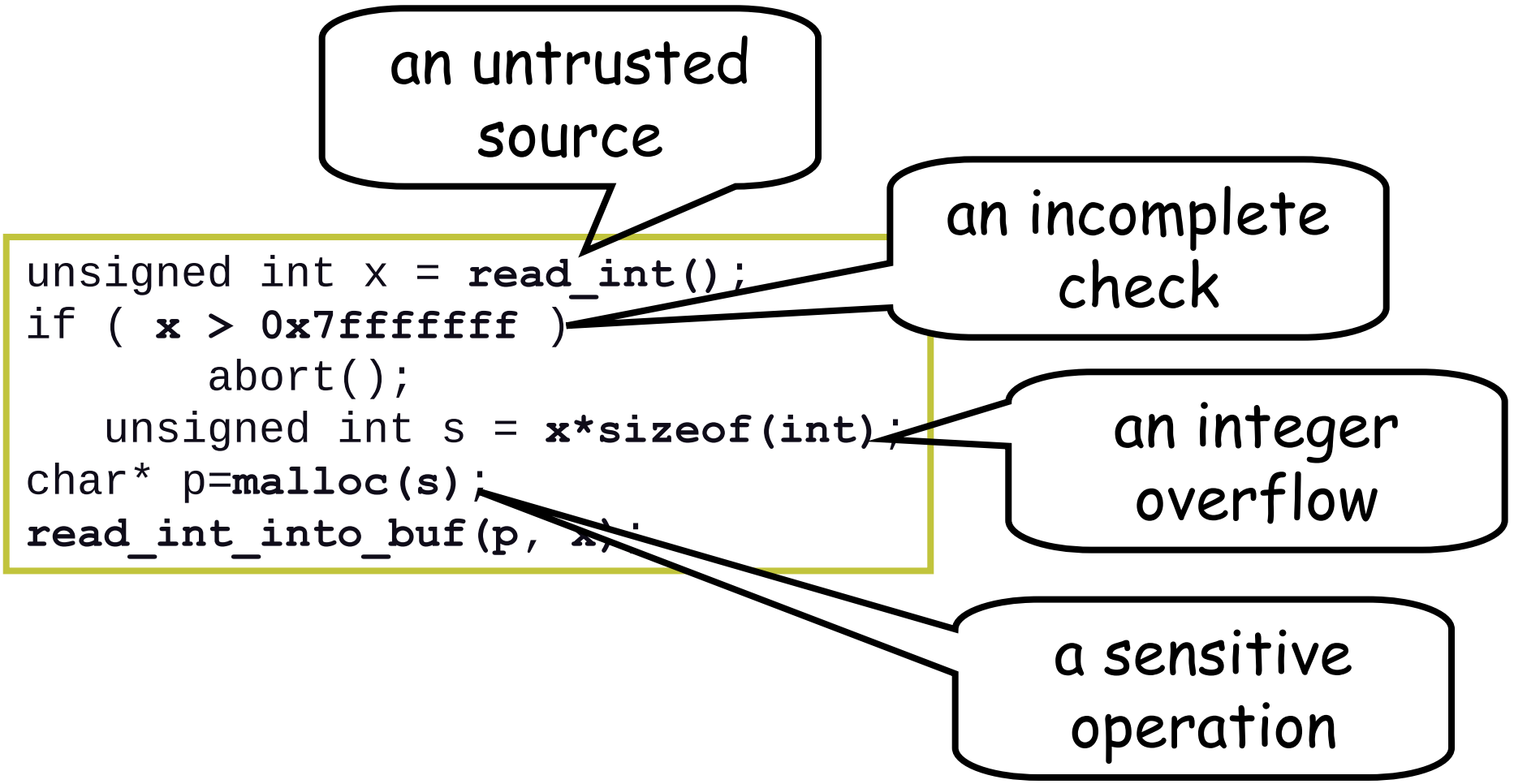
an untrusted source

an incomplete check

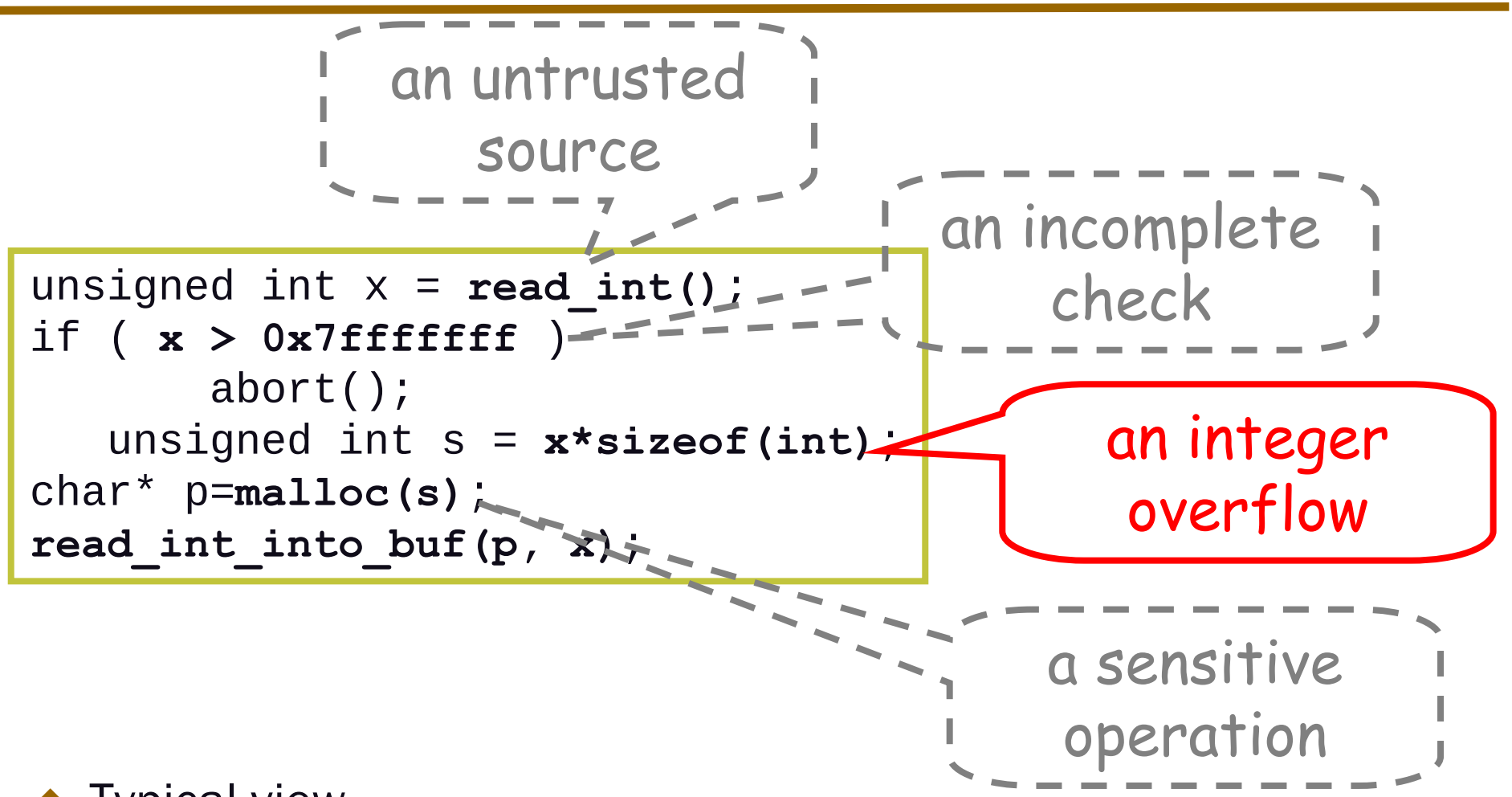
an integer overflow

a sensitive operation

What's the essential feature of integer overflow vulnerabilities?



What's the essential feature of integer overflow vulnerabilities?

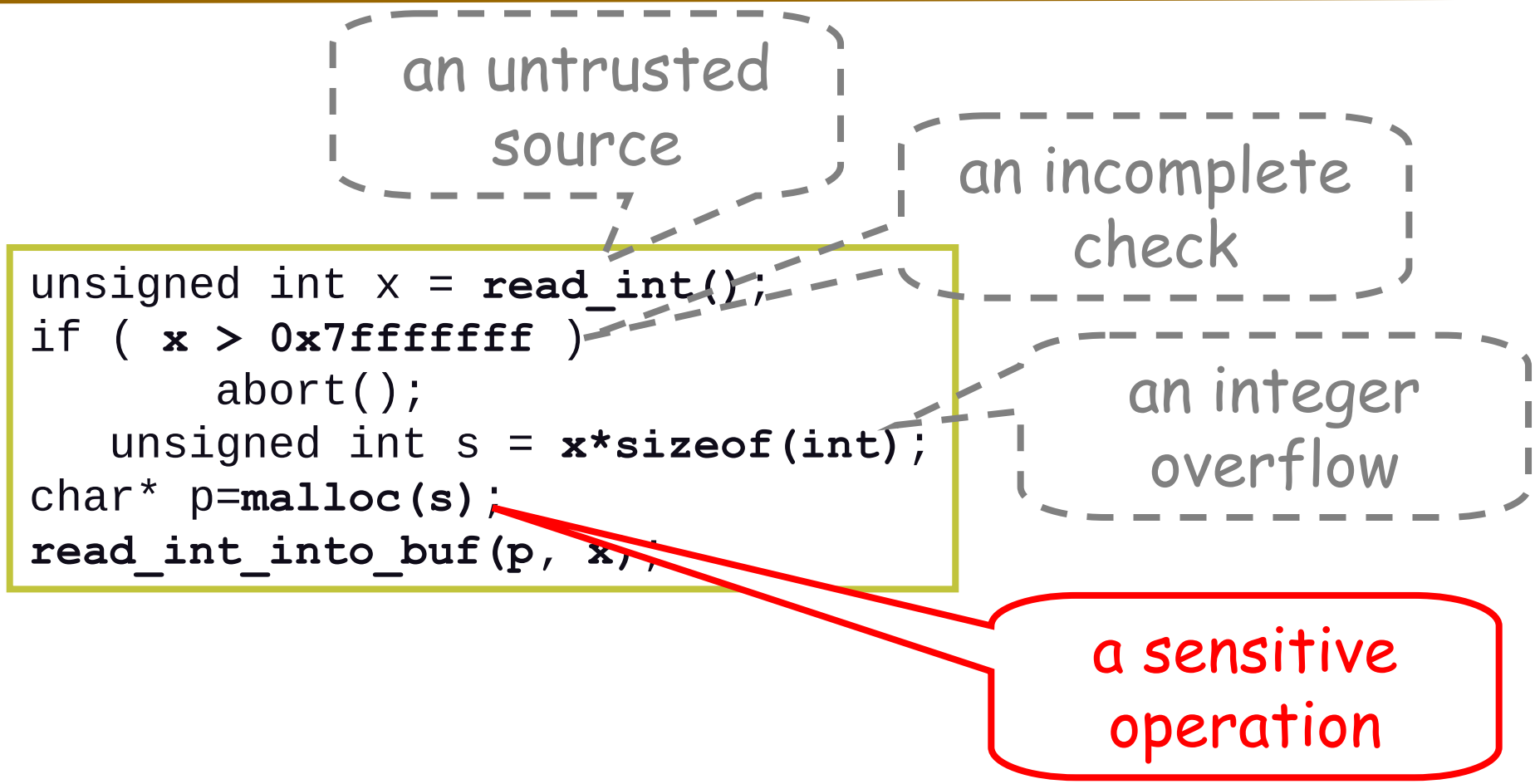


- Typical view
  - the essential feature is the actual overflow itself

Integer Overflow != Integer Overflow Vulnerability

- Case 1: The overflowed value is NOT used in any sensitive operation
  - e.g. TCP sequence number rolls back per 4GB
- Case 2: The overflowed value is NOT tainted
  - Most untainted integer overflows are on purpose, i.e., benign overflows, e.g. computing random seeds
- So Integer overflow itself is not the essential part of the vulnerability

What's the essential feature of integer overflow vulnerabilities?



- The essential feature is those sensitive operations which use some tainted overflowed data.

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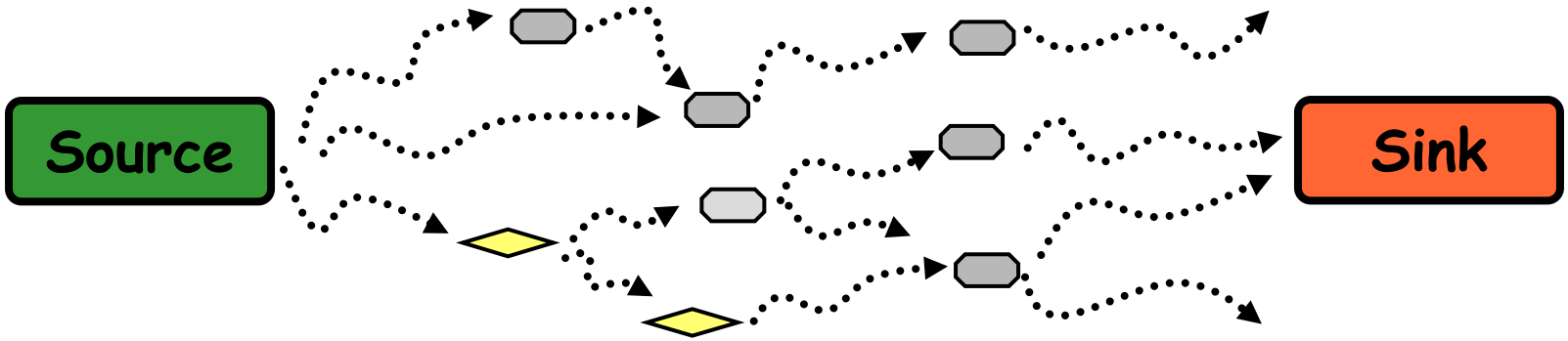
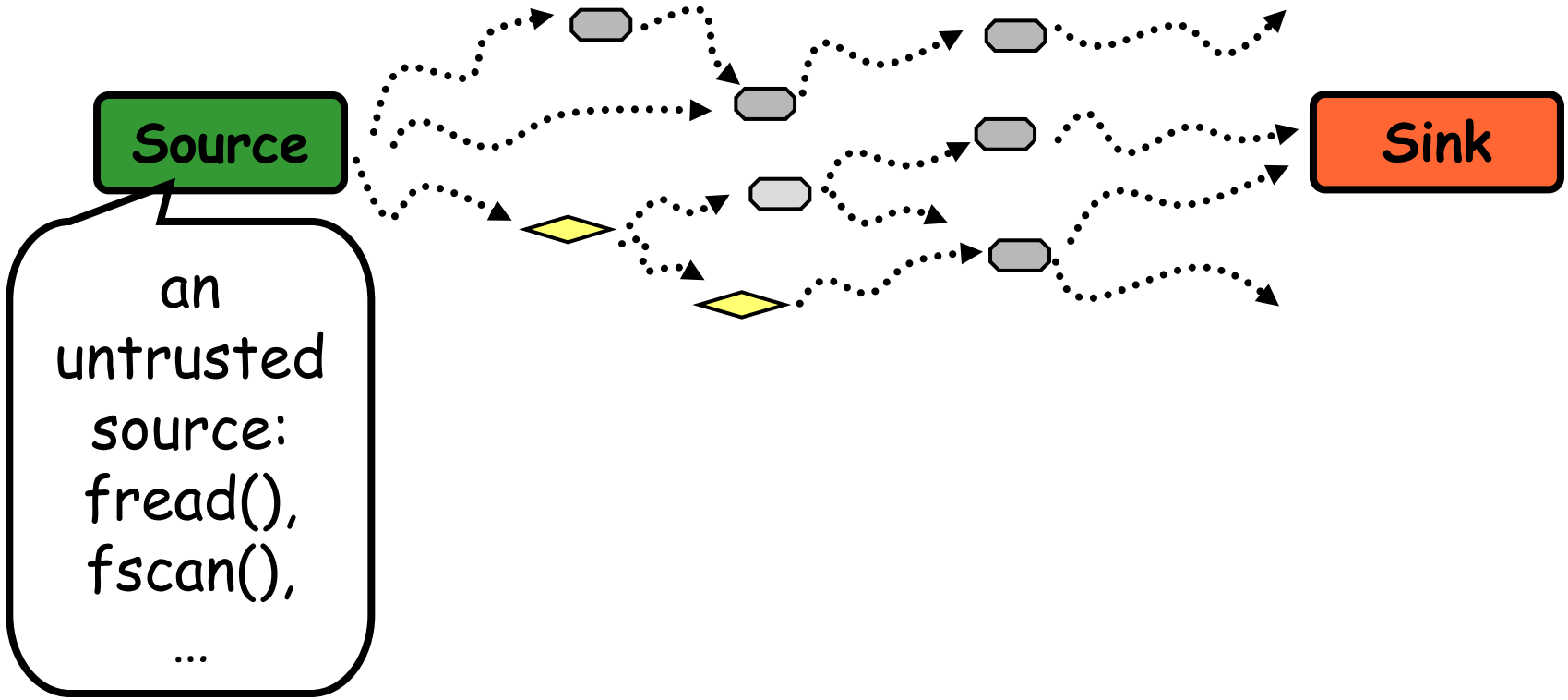
Modeling Integer Overflow Vulnerability

- An instance of taint-based problem



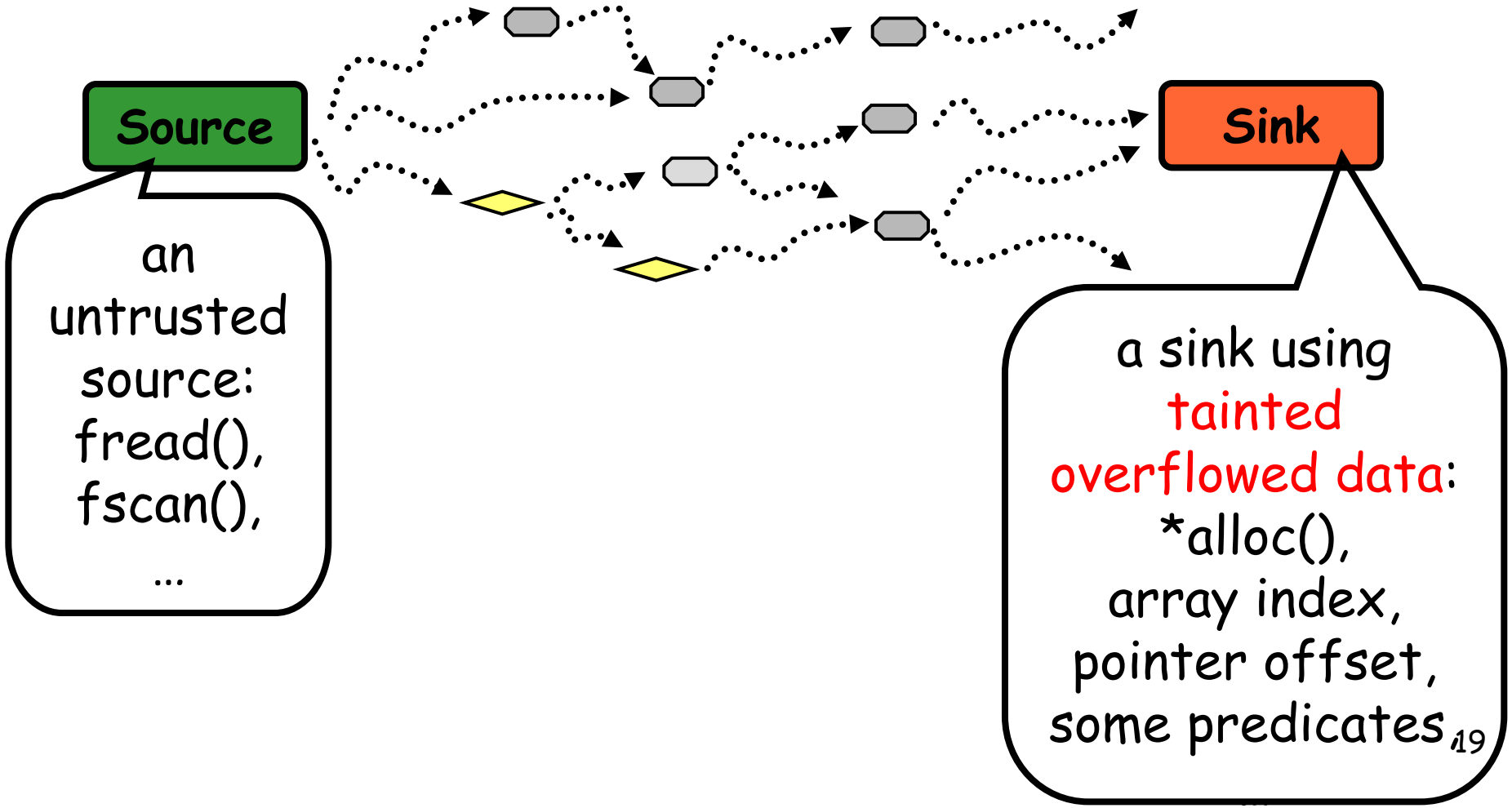
Modeling Integer Overflow Vulnerability

- An instance of taint-based problem



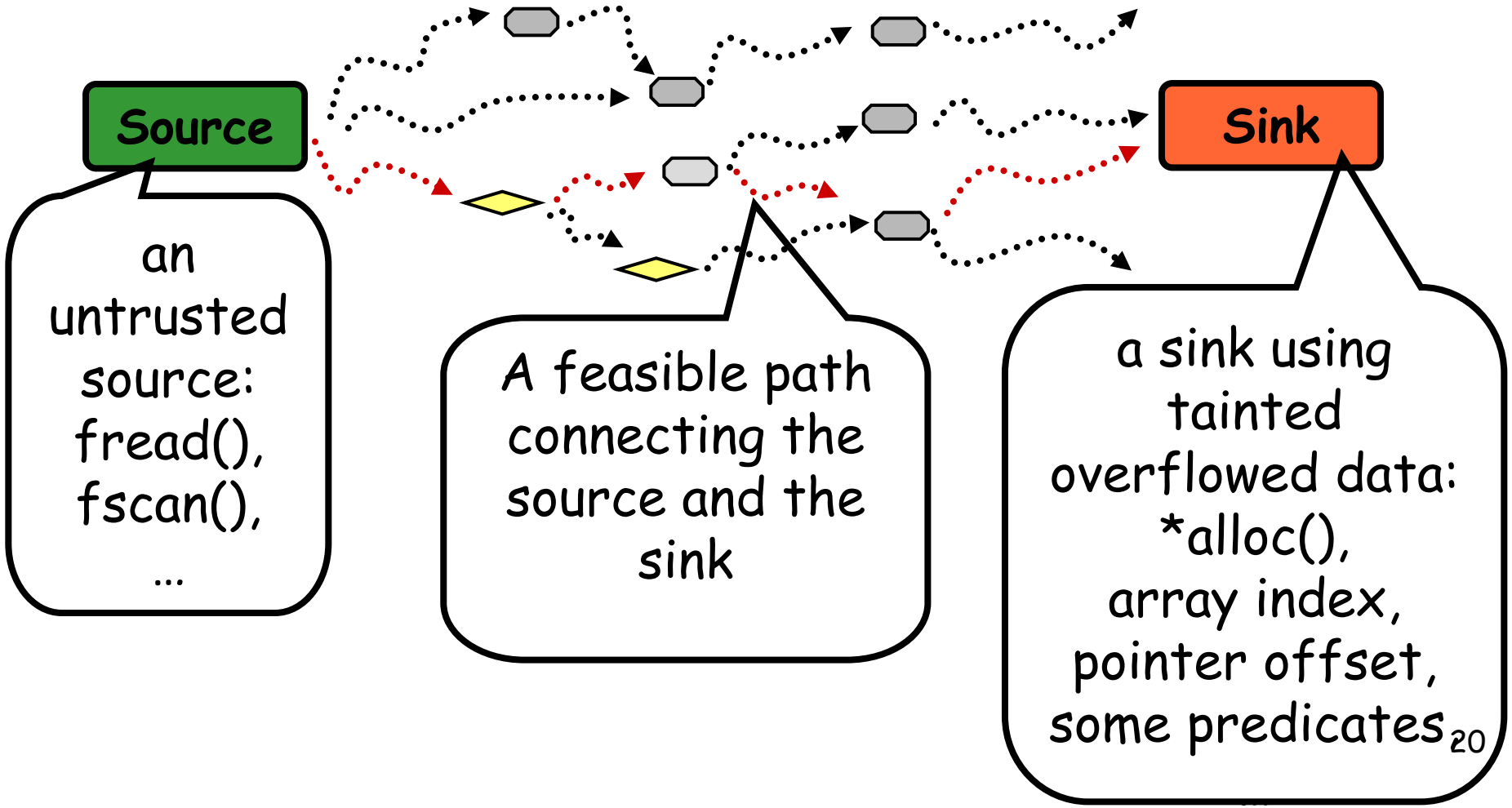
Modeling Integer Overflow Vulnerability

- An instance of taint-based problem



Modeling Integer Overflow Vulnerability

- An instance of taint-based problem



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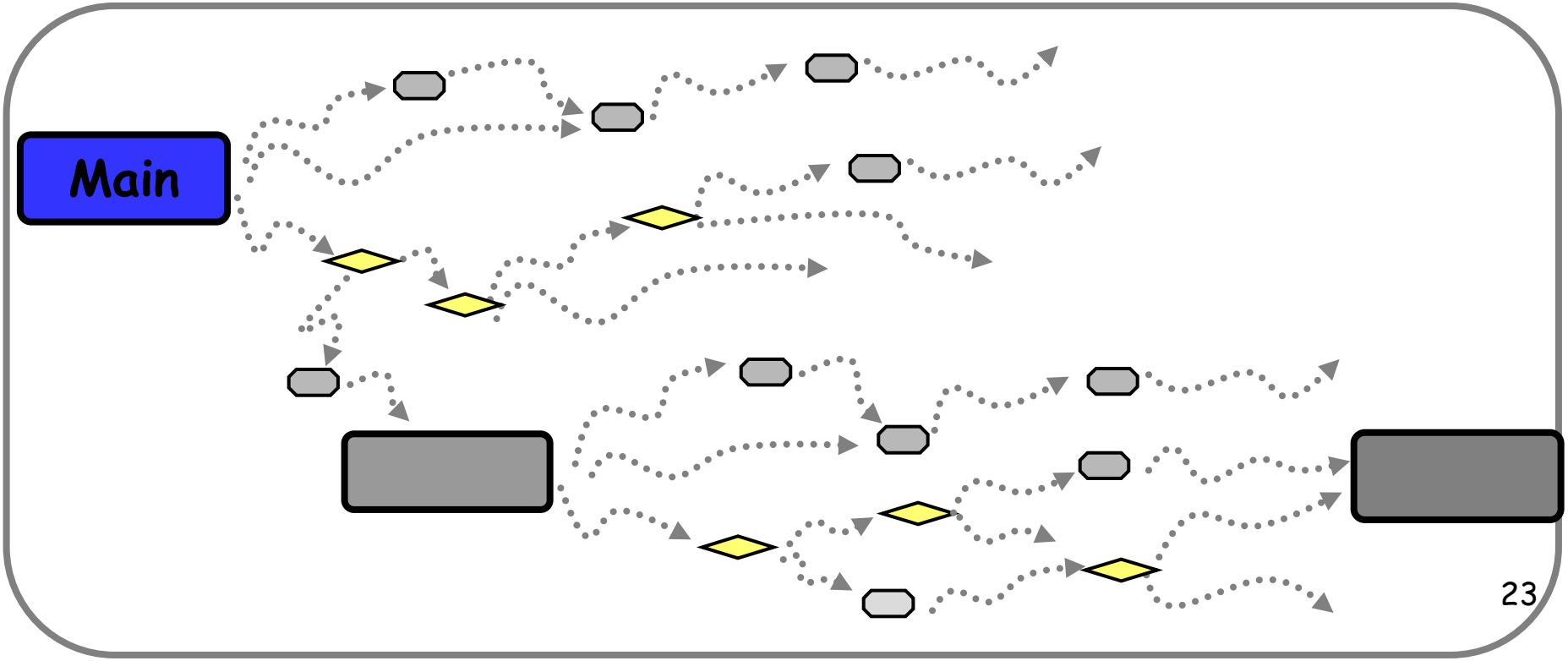
Natural Approach

- Based on general static taint analysis
- Given a binary program

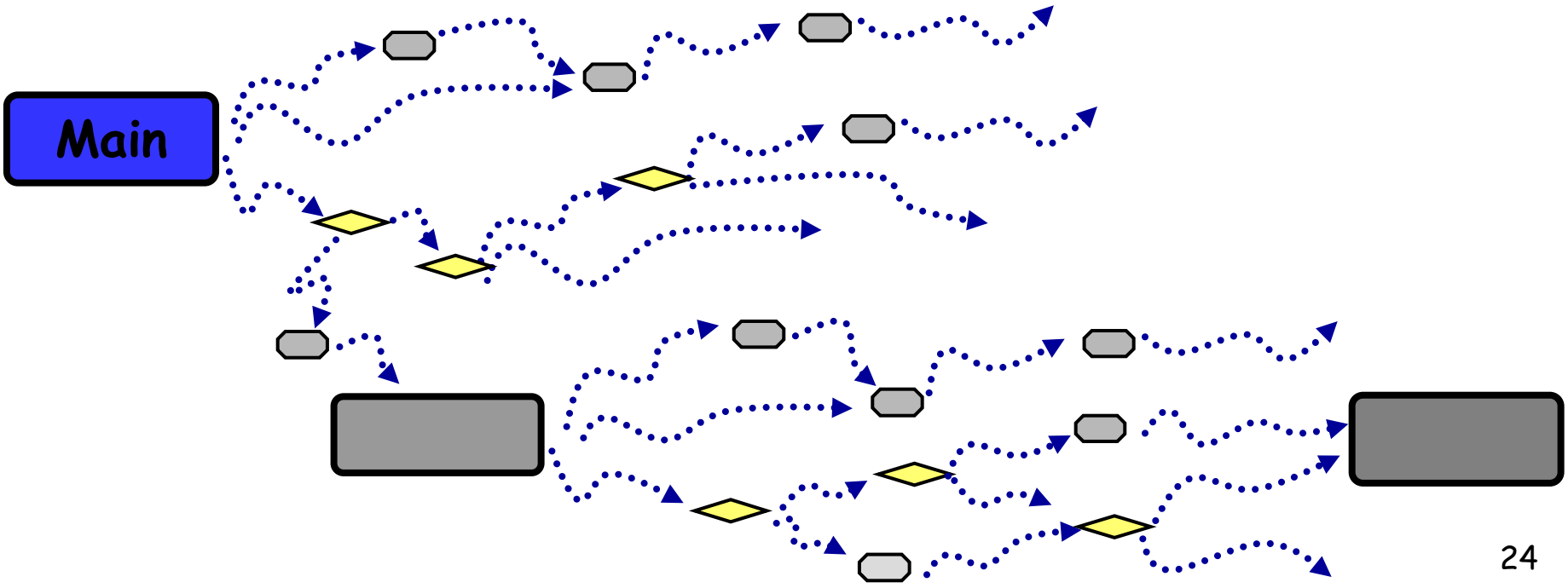
Natural Approach

- Decompile the binary program
  - Generate the intermediate representations, call graphs, CFGs, …



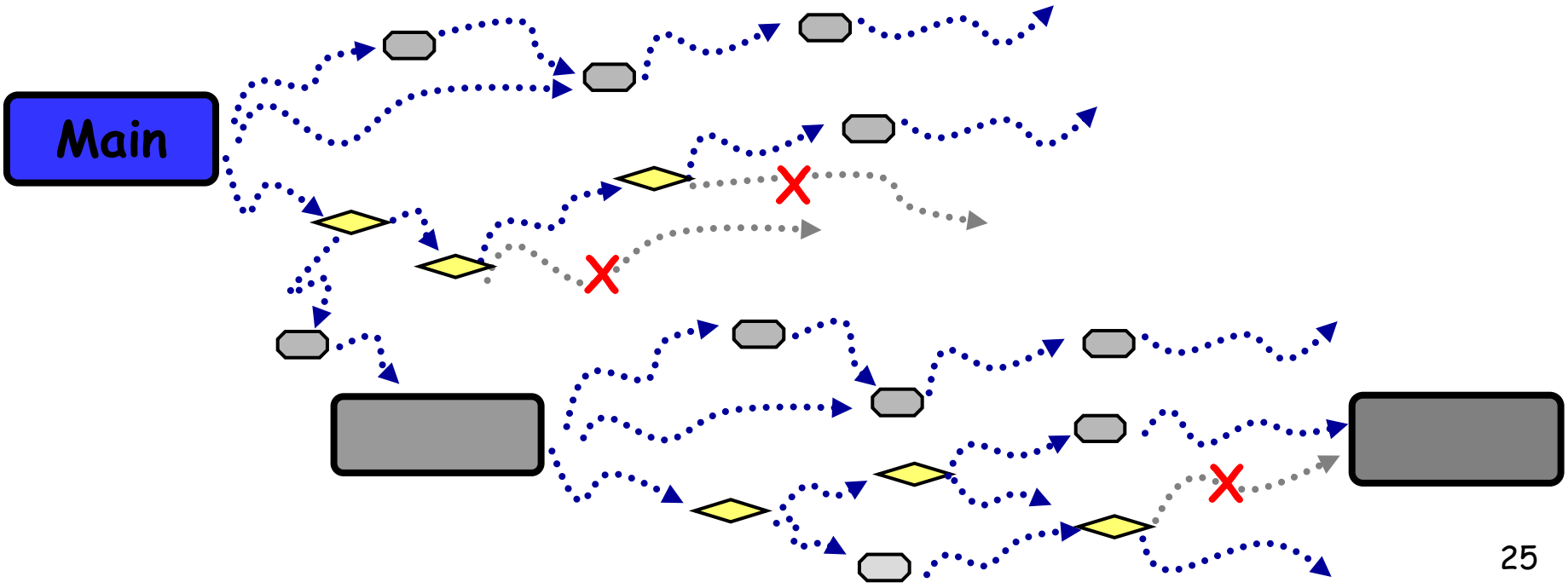
Natural Approach

- Decompile
- Traverse all paths from main() using symbolic execution



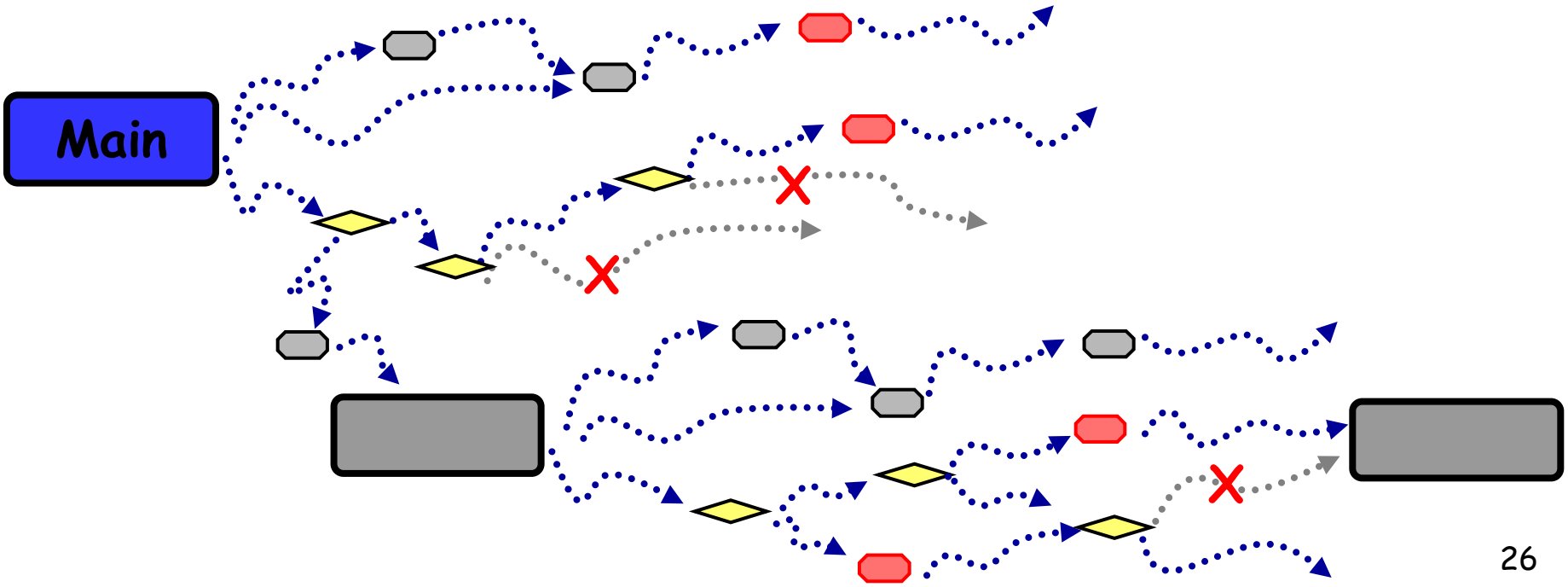
Natural Approach

- Decompile
- Traverse, Prune infeasible paths, whose path constraints cannot be satisfied, during traversing



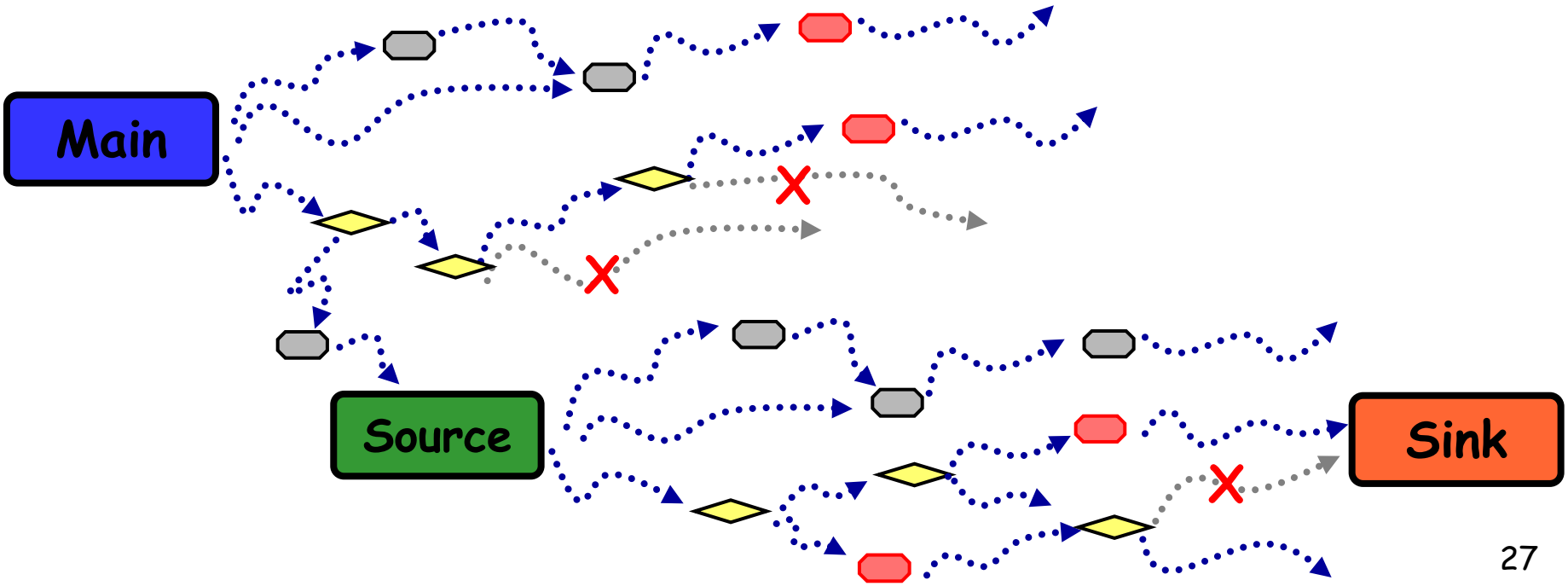
Natural Approach

- Decompile
- Traverse, Prune, Check possible integer overflows during traversing



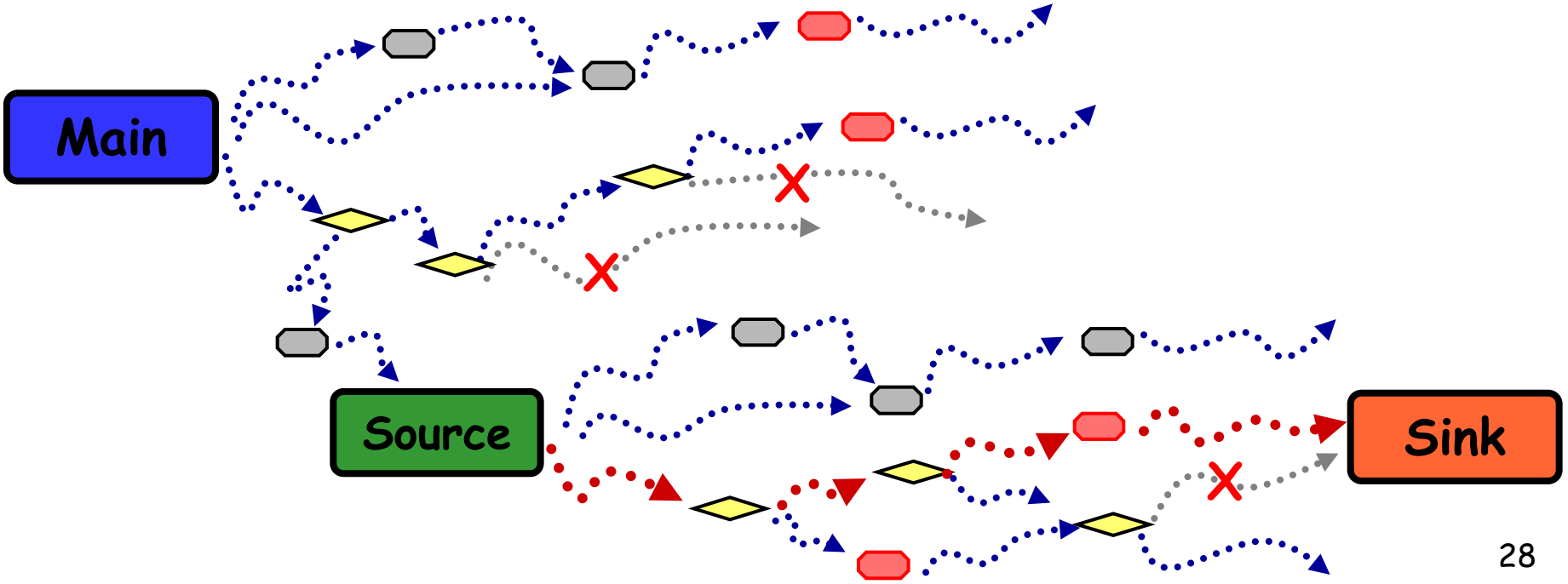
Natural Approach

- Decompile
- Traverse, Prune, Check, Tag sources and sinks during traversing



Natural Approach

- Decompile
- Traverse, Prune, Check, Tag
- Output suspicious paths in which tainted overflowed data used in sinks



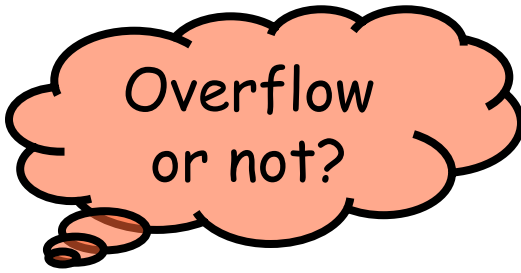
Does this natural approach work efficiently?

- Major Challenges
  - 1. Lack of type information
  - 2. Path explosion
  - ……

Challenge 1. Lack of type information

- During traversing, how can we determine there is an overflow or not?

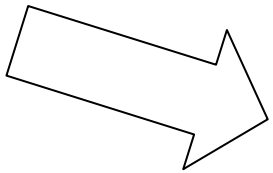
```
mov    eax, 0xffffffff    ; eax = 0xffffffff or -1
add    eax, 2             ; eax = eax + 2
```



How to solve this?

- Lazy check : only check integer overflows used in sinks

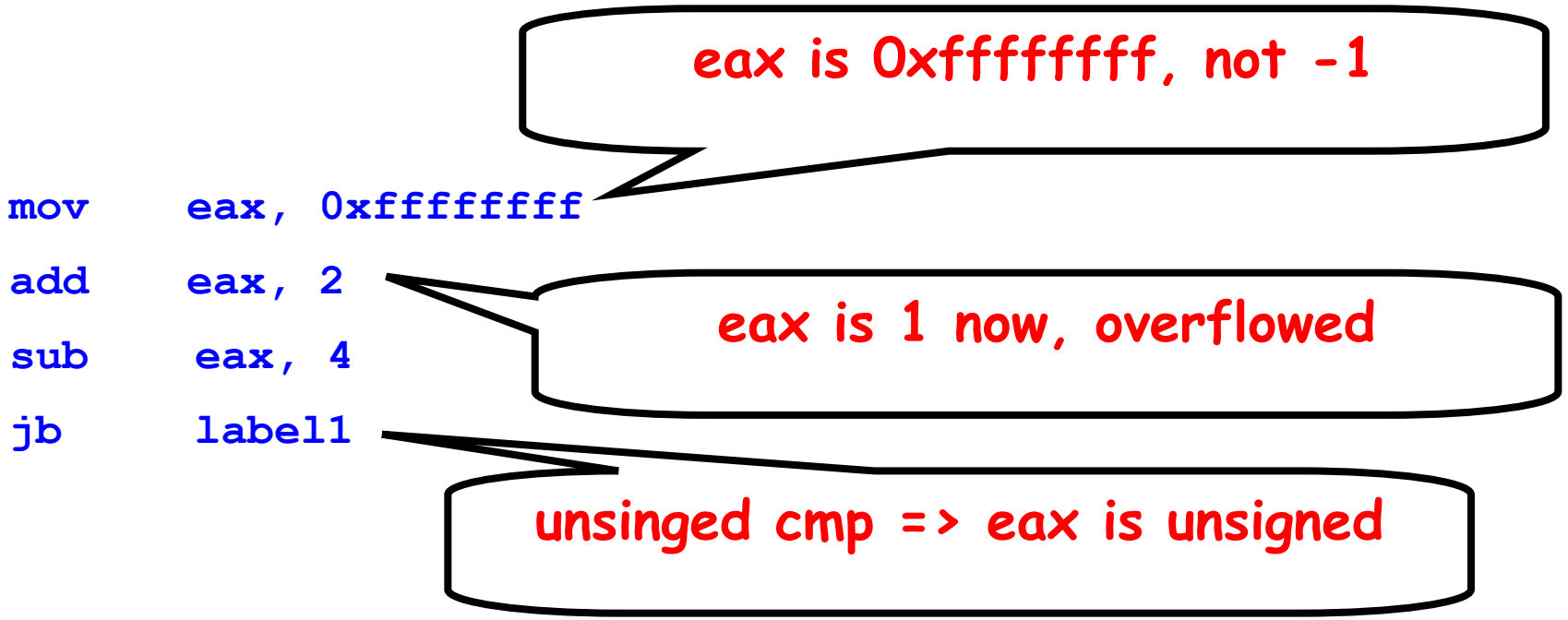
- Decompile
- Traverse, Prune, Check, Tag
- Output



- Decompile
- Traverse, Prune, Tag, Check,
- Output

Lazy check

- Only check integer overflows used in sinks



Benefit of Lazy check

- Useful type information hints
  - Signed/unsigned comparisons

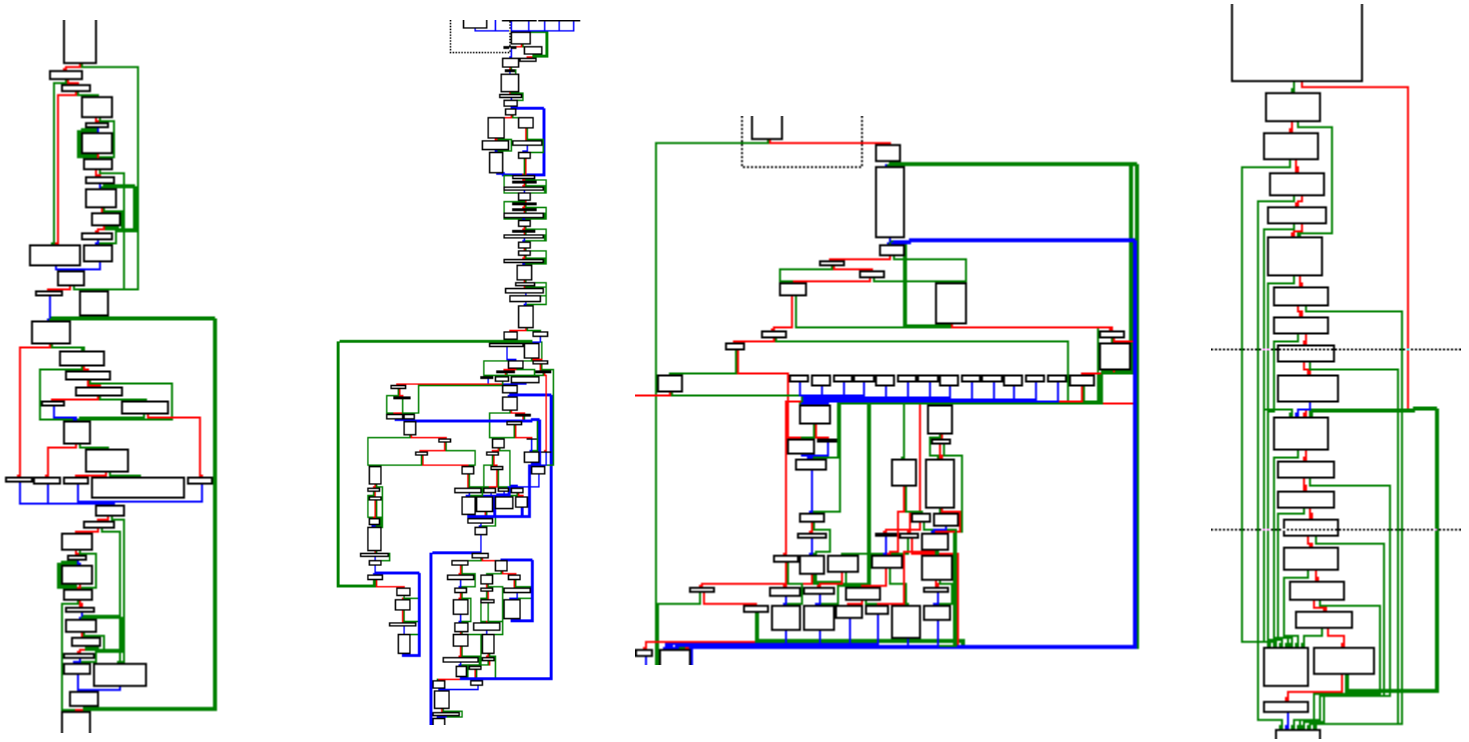
    signed: JG, JGE, JNL, JNGE, JLE, JNG, JE, JNE

    unsigned: JA, JAE, JNB, JB, JNAE, JBE, JNA, JE, JNE
  - void *calloc(size_t nmemb, size_t size);
  - void *malloc(size_t size);
  - …

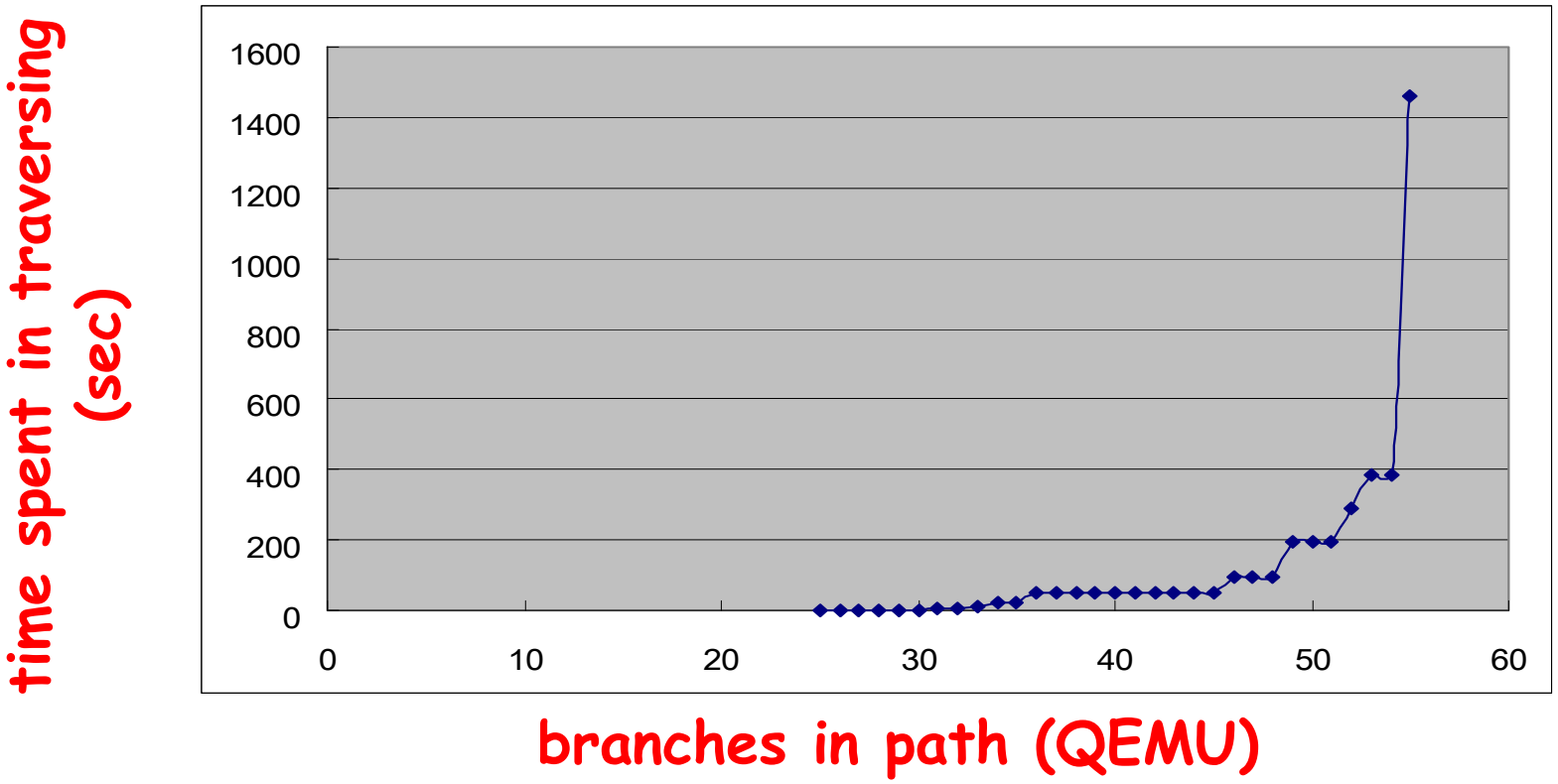
- Much less checks, much more efficiency

Challenge 2. Path explosion

- We need path-sensitive analysis, but the number of paths through software is very large.



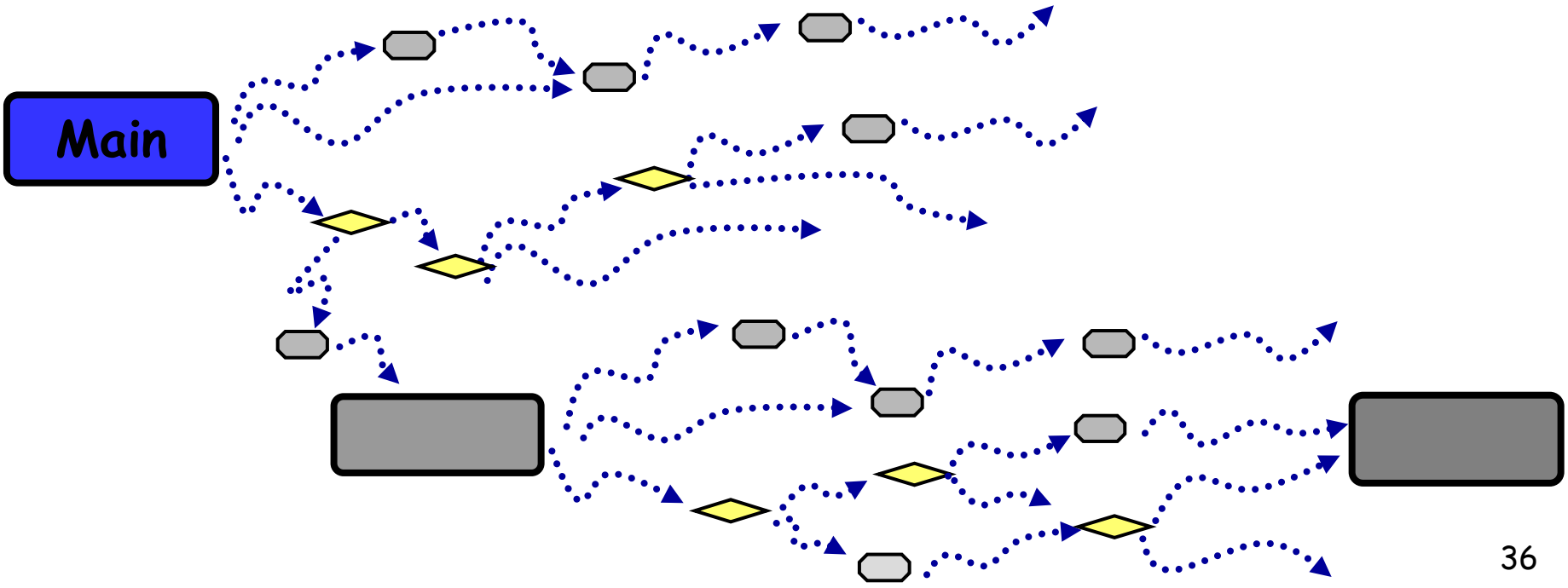
Exponential Traversing Time



- Only pruning during execution is not enough

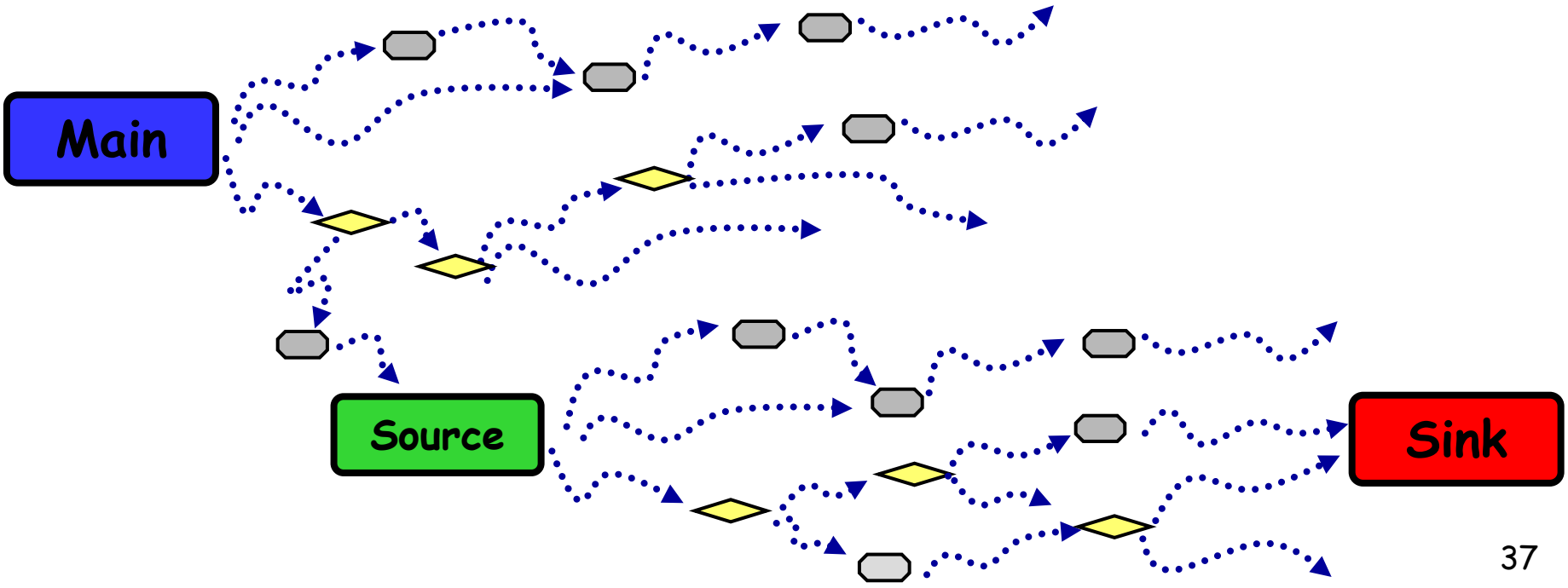
Solution: Pre-pruning before traversing

- Only consider paths between sources and possible sinks



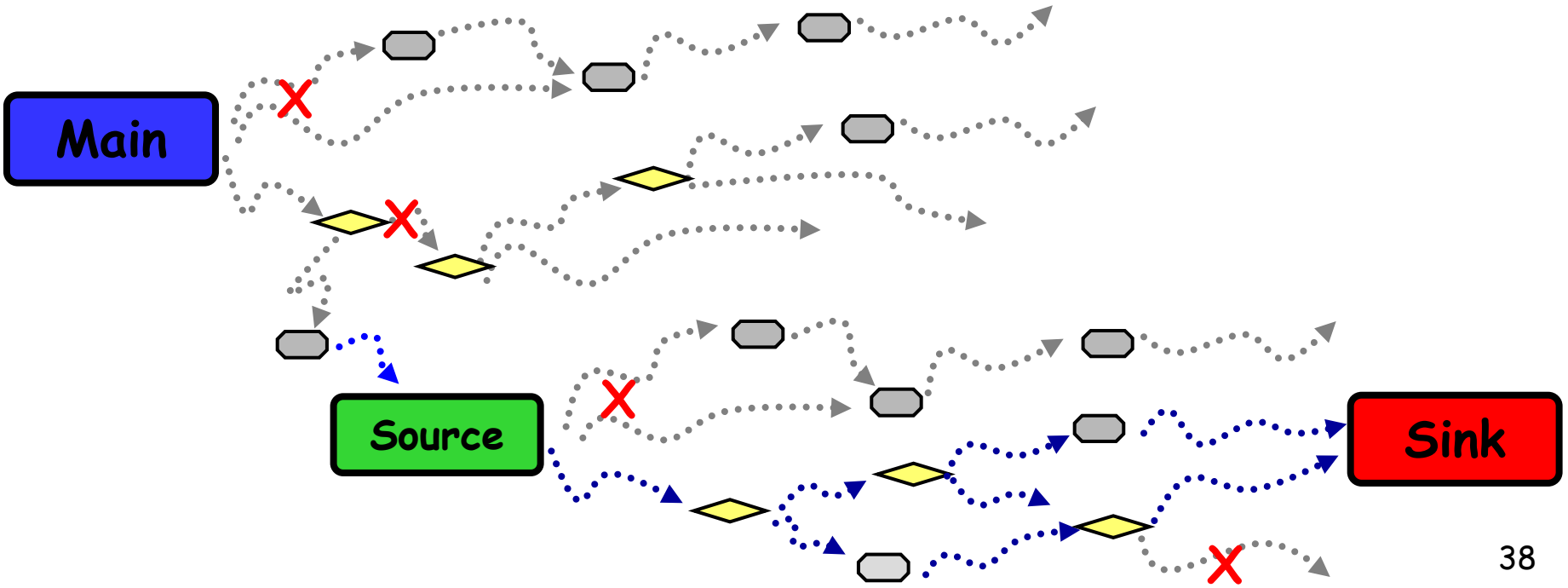
Pre-pruning

- Tag sources and possible sinks before traversing



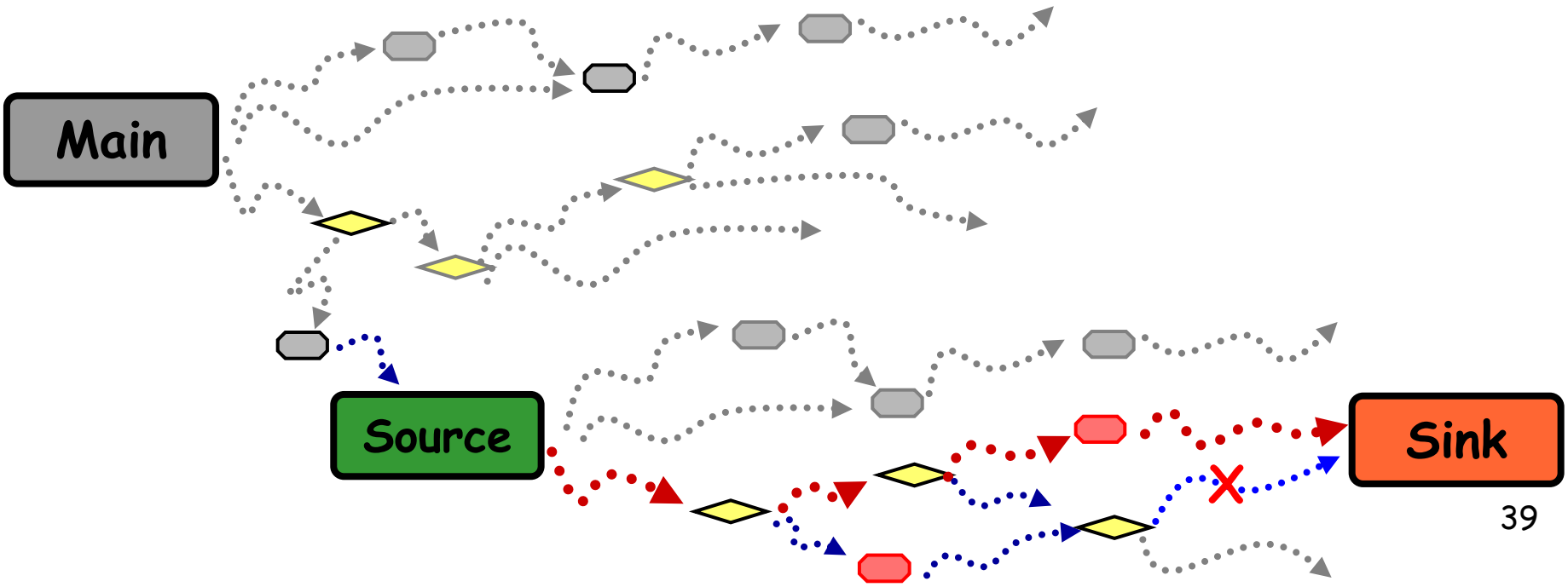
Pre-pruning

- Tag
- Cut off those paths irrelevant to sources and sinks using some inter-function slicing algorithms



Put it all together

- Decompile
- Tag, Pre-prune
- Traverse, Prune, Lazy Check
- Output suspicious paths

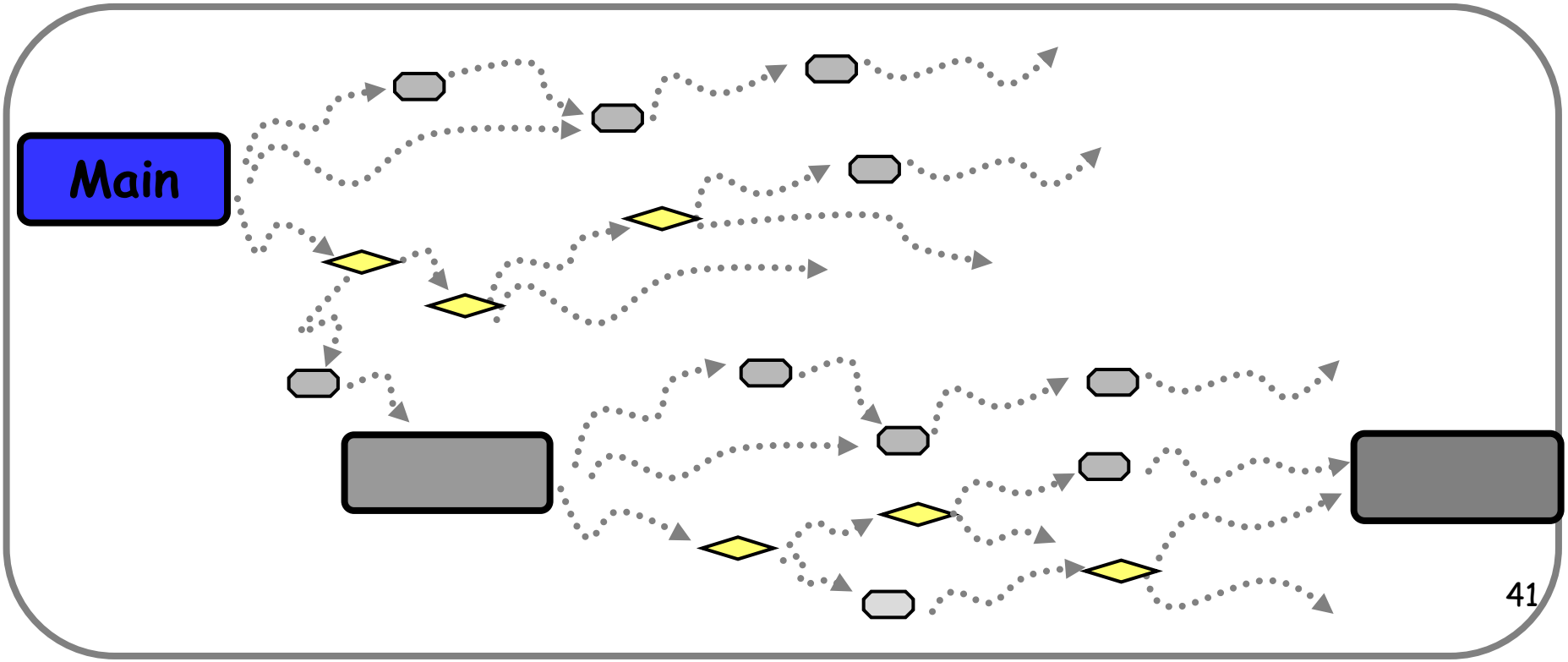


Put it all together

- Given a binary program

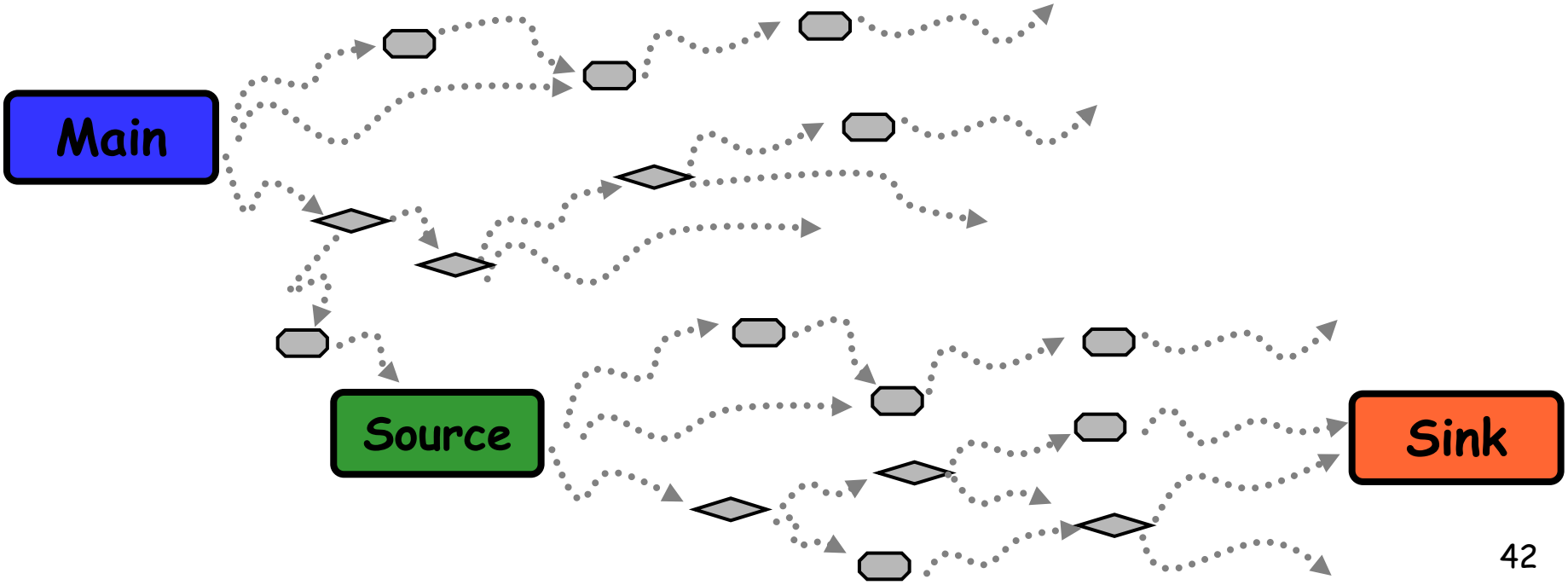
Put it all together

- Decompile the program
  - Generate the IR, call graph, CFGs, and so on



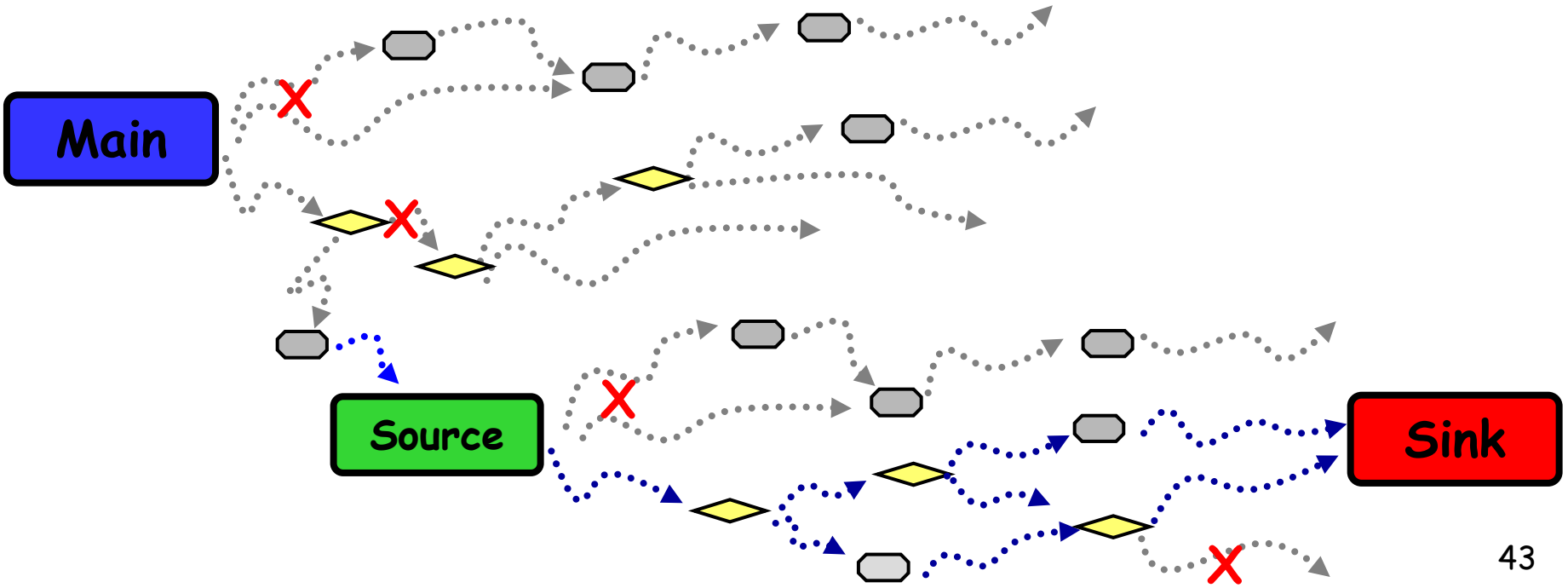
Put it all together

- Decompile
- Tag possible sources and sinks



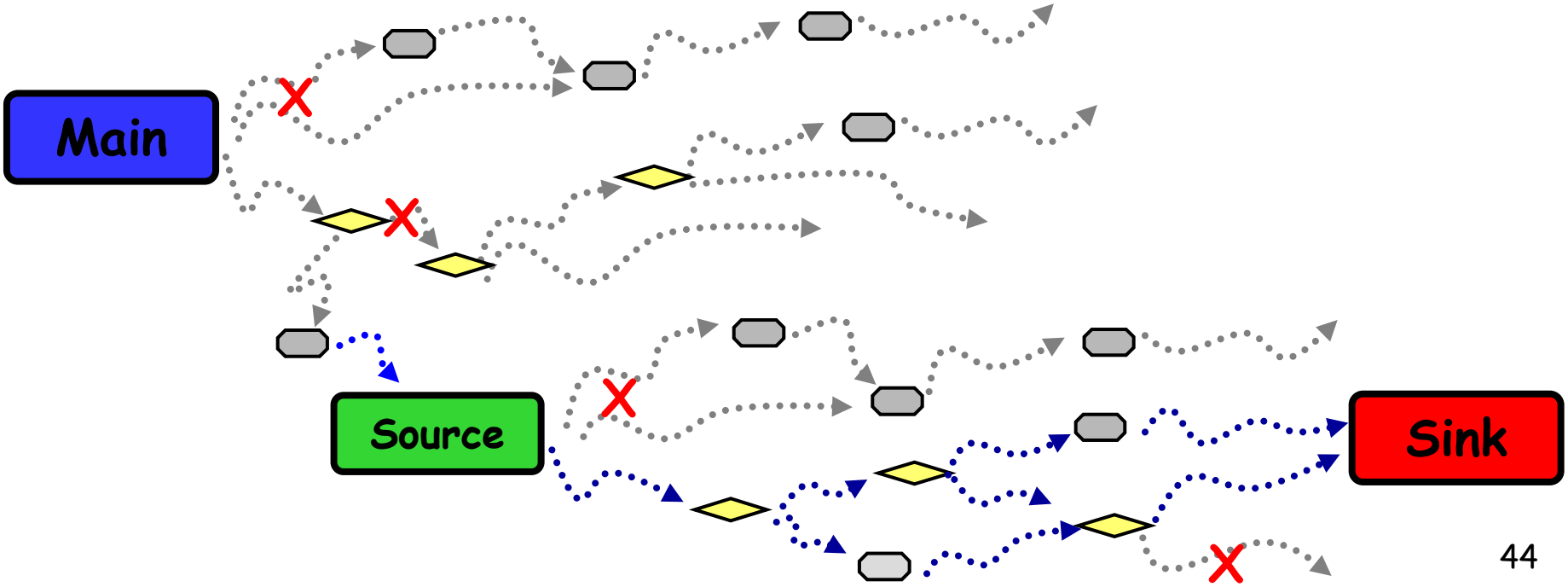
Put it all together

- Decompile
- Tag, Pre-prune: Cut off those paths irrelevant to sources and sinks



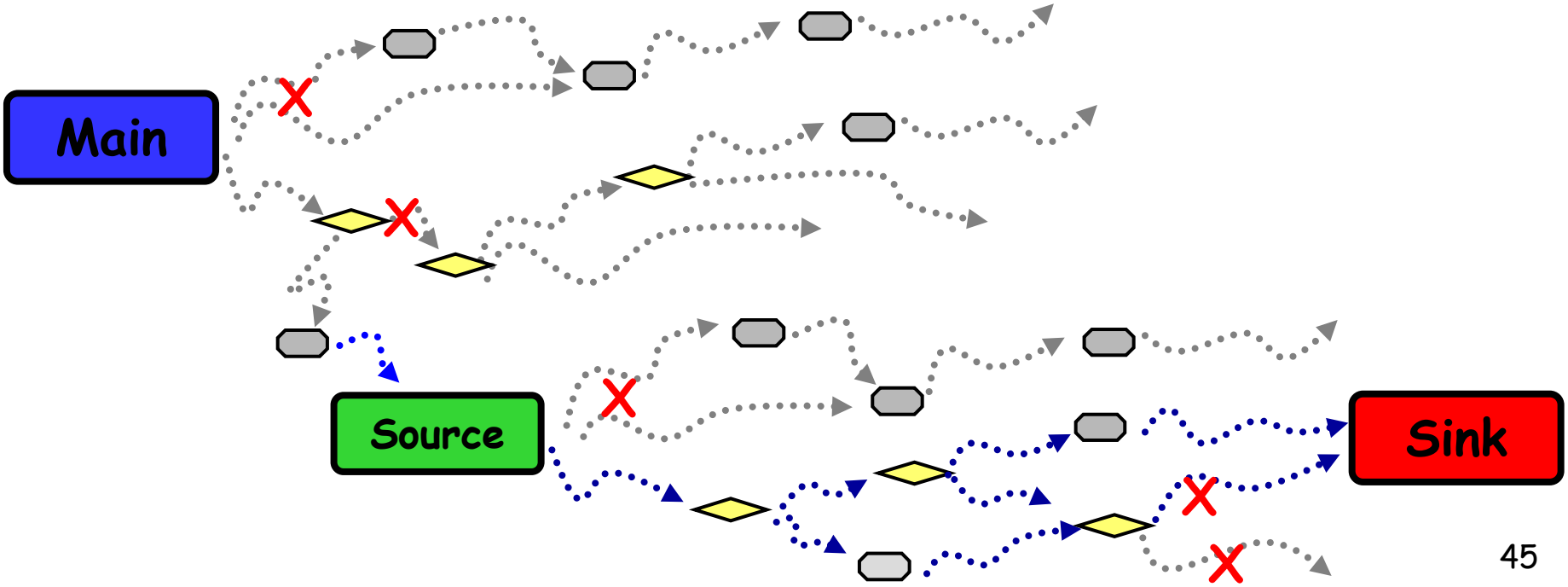
Put it all together

- Decompile
- Tag, Pre-prune
- Traverse paths left using symbolic execution



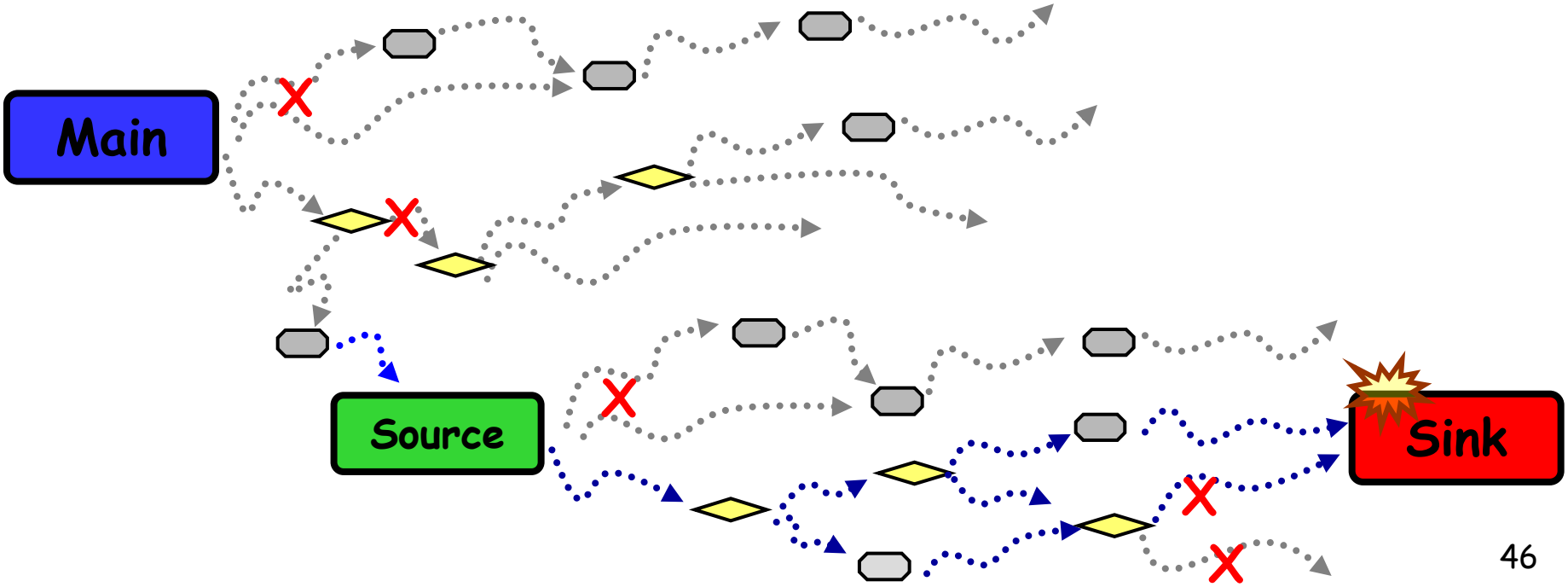
Put it all together

- Decompile
- Tag, Pre-prune
- Traverse, Prune infeasible paths during traversing



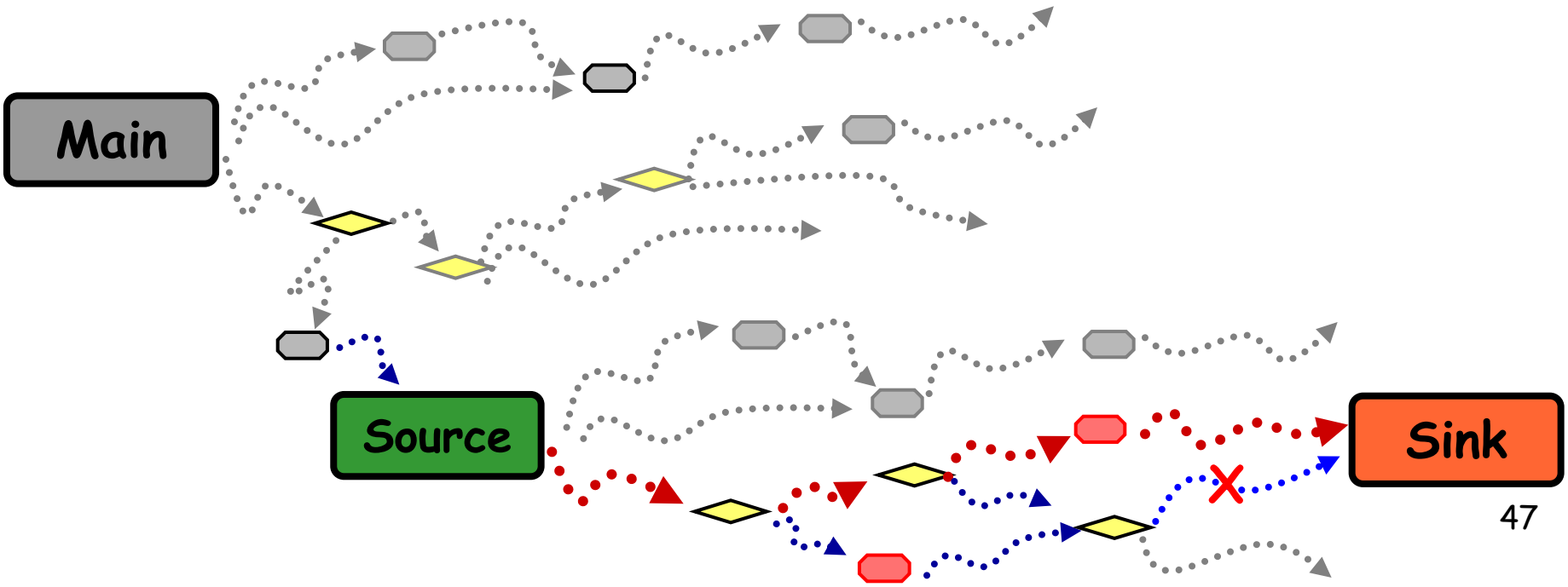
Put it all together

- Decompile
- Tag, Pre-prune
- Traverse, Prune, Lazy Check : check integer overflows used in sinks



Put it all together

- Decompile
- Tag, Pre-prune
- Traverse, Prune, Lazy Check
- Output suspicious paths



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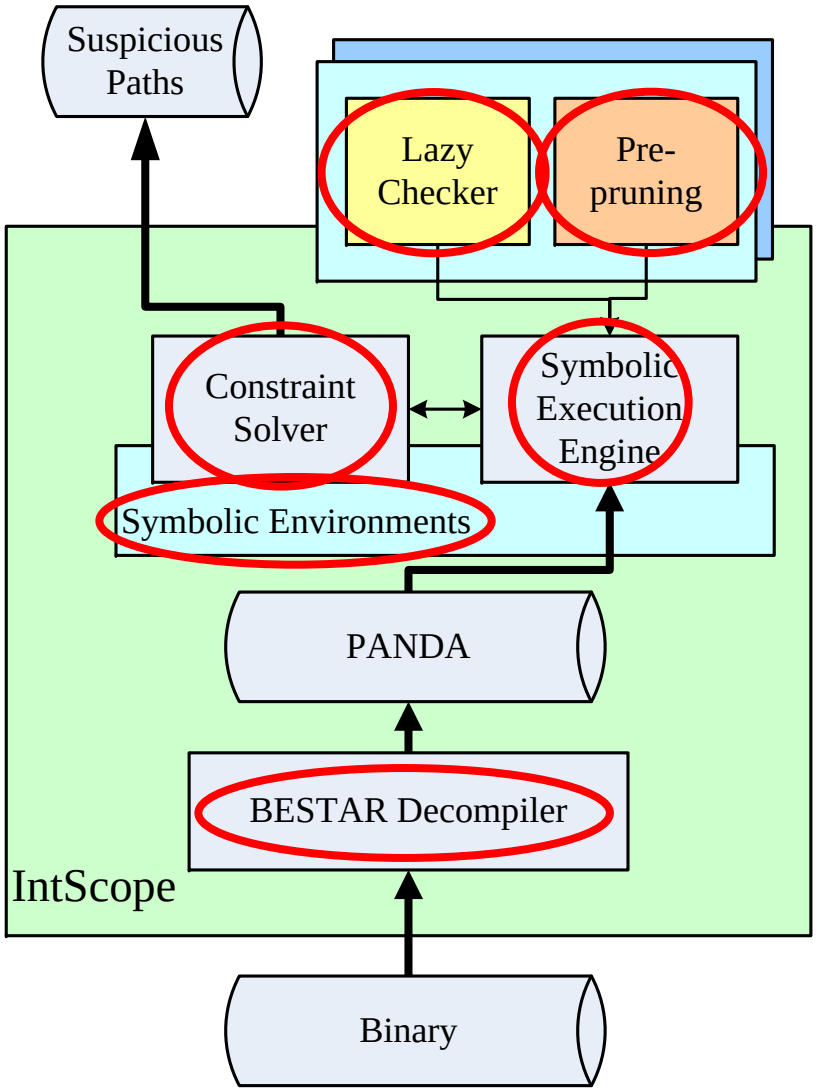
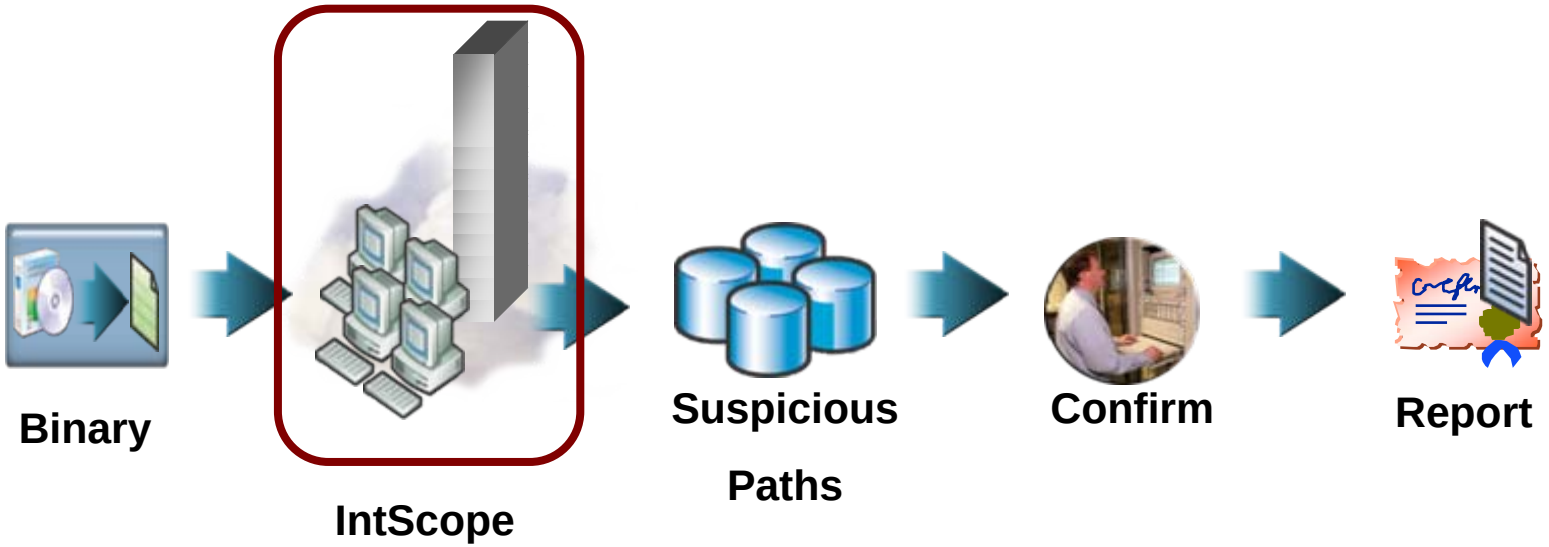
IntScope Architecture



- IntScope
  - Decompiler
    - ✓ BESTAR [SAS2007]
  - Cut off irrelevant paths
    - ✓ Pre-pruning Engine
  - Symbolic Execution
    - ✓ Environment
    - ✓ Engine
  - Pruning during traversing
    - ✓ Constraint Solver
  - Lazy Checker
- 3rd Party Modules
  - Disassembler: IDA Pro
  - CAS: GiNaC
  - Constraint Solver: STP

How to use IntScope



Evaluation

- Two Windows DLLs
  - GDI32.dll
  - comctl32.dll
- Several widely used applications
  - QEMU, Xen
  - Media players
    - ✓Mplayer
    - ✓Xine
    - ✓VLC
    - ✓FAAD2
    - ✓MPD
  - Others
    - ✓Cximage, Hamsterdb, Goom

QEMU
open source processor emulator

Xen

VideoLAN

soutient
la campagne d'adhésion de
For the French speaking public

April
promouvoir et défendre
le logiciel libre

Cximage

HAMSTER DB
embedded database

Effectiveness

- Detected known integer overflow bugs in Windows DLLs
- Detected 20+ zero-day integer overflow vulnerabilities
  - Confirmed by developers or concrete test cases
  - Some projects have released patches
- We have reported vulnerabilities in QEMU and FAAD2 to French Security Incident Response Team (FrSIRT)
  - *CVE-2008-4201*
  - *FrSIRT/ADV-2008-2919*
  - *……*

Effectiveness

Name	Version	Entry Function	Paths#	Total#	Confirmed #	Suspicious#
GDI32.dll	5.1.2600.2180	CopyMetaFile	452	3	1	2
comctl32.dll	5.82.2900.2180	DSA_SetItem	3	2	1	1
QEMU Xen	0.9.1 3.2.1	bochs_open	3	1	1	0
		cloop_open	1	1	1	0
		parallels_open	2	1	1	0
		qcow_open(for qcow2 format)	3	1	1	0
		vmdk_open	20	2	1	1
		vpc_open	1	1	1	0
Xine	1.1.15	ff_audio_decode_data	10	1	1	0
		process_commands	2	2	2	0
Xine-ui	0.99.5	_LoadPNG	4	1	1	0
MPlayer	1.0rc2	dumpsub_gab2	1	1	1	0
		init_registry	3	1	1	0
Mpd	0.13.2	mp4_decode	2	1	1	0
Goom	2k4	gsl_read_file	1	1	1	0
Cximage	600_full	ConvertWmfFiletoEmf	1	1	1	0
faad2	2.6.1	decodeMP4file	36	3	2	1
		mp4ff_read_stts	1	1	1	0
Hamsterdb	1.0.4	btree_find_cursor	3	1	1	0

- Among 26 integer overflow vulnerability points, 21 of them have been confirmed

Efficiency

- AMD Opteron Server (2.6 GHz) with 8GB memory

Name	Executable	File Size	Binary-to-IR time (seconds)	IR Size	Traversing Time (seconds)
GDI32.dll	GDI32.dll	271KB	614	7.61 MB	574
comctl32.dll	comctl32.dll	597 KB	1131	13.7 MB	0.1
QEMU	Qemu-img	341 KB	124	12.8 MB	358
Xine	cdda_server	14.5 KB	4	116 KB	26
	xine	966 KB	590	12.9 MB	327
Mplayer	avisubdump	14.2 KB	1	36.8 KB	0.3
MPD	mpd	243 KB	131	2.74 MB	667
GOOM	libgoom2.so	439KB	94	1.42 MB	445
faad2	faad	57.6 KB	29	693 KB	113
Hamstedb	libhamsterdb.so	260 KB	164	3.46 MB	426
Average		320.3KB	288.2	5.46MB	293.6

- Average time : about 5 min
- Longest time : < 12 min

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- Intuition & Challenge
- Implementation & Evaluation
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Related Work

- w/ source code
  - Run-time Protection
    - ✓ Safe integer libraries
    - ✓ RICH [NDSS'07]
    - ✓ GCC
  - Dynamic and/or Static analysis
    - ✓ Range checker [S&P'02]
    - ✓ CQual[PLDI02], EXE[CCS06], KLEE[OSDI08], DART[PLDI05], CUTE[FSE05]
- w/o source code
  - Fuzzing
    - ✓ SAGE [NDSS'08]
    - ✓ Catchconv [Molnar and Wagner, Berkeley]
  - Static analysis of integer overflows using sym exec <= IntScope

Outline

- Motivation
- Case Study
- Modeling
- Intuition & Challenge
- Implementation & Evaluation
- Related Work
- Conclusion

Conclusion

- IntScope
  - Modeling Integer Overflow Vulnerability as a taint-based problem
  - Lazy Check : only check integer overflows lazily at sinks
  - Pre-prune : prune paths irrelative to sources and possible sinks before traversing
  - Detect 20+ Zero-day integer overflow vulnerabilities

Questions?

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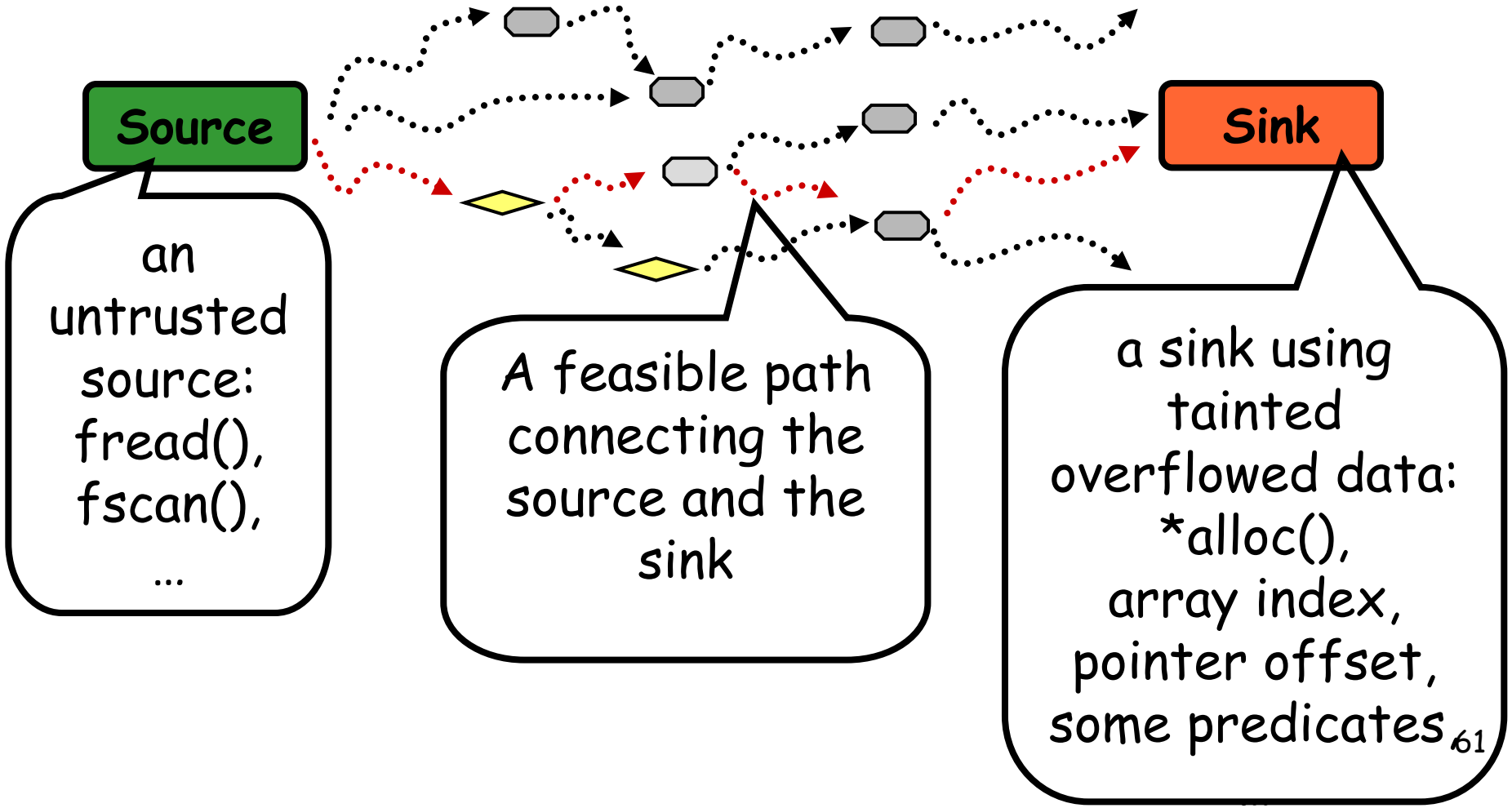
Backup slides

Modeling Integer Overflow Vulnerability

- An instance of taint-based problem



Suspicious Paths

- IntScope is a static analysis tool, so it may generate false positives.
  - Missing of the constraints between inputs.
  - Lack of global information
  - Imprecise symbolic execution

- For each vulnerability, if we cannot construct a concrete test case to trigger it, we leave it as a suspicious one.

False positives

- IntScope is a static analysis tool, so it may generate false positives.
  - Missing of the constraints between inputs.
  - Lack of global information
  - Imprecise symbolic execution
- It's hard to prove an alert is a real vulnerability
  - we need to construct a concrete test case to trigger the vulnerability.
- If we can not construct such test cases, we take these alerts as suspicious ones.