Operating Systems Security

PROFESSIONAL EDUCATION

CSAIL
MIT COMPUTER SCIENCE AND ARTIFICIAL INTELLIGENCE LABORATORY

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Operating Systems Security

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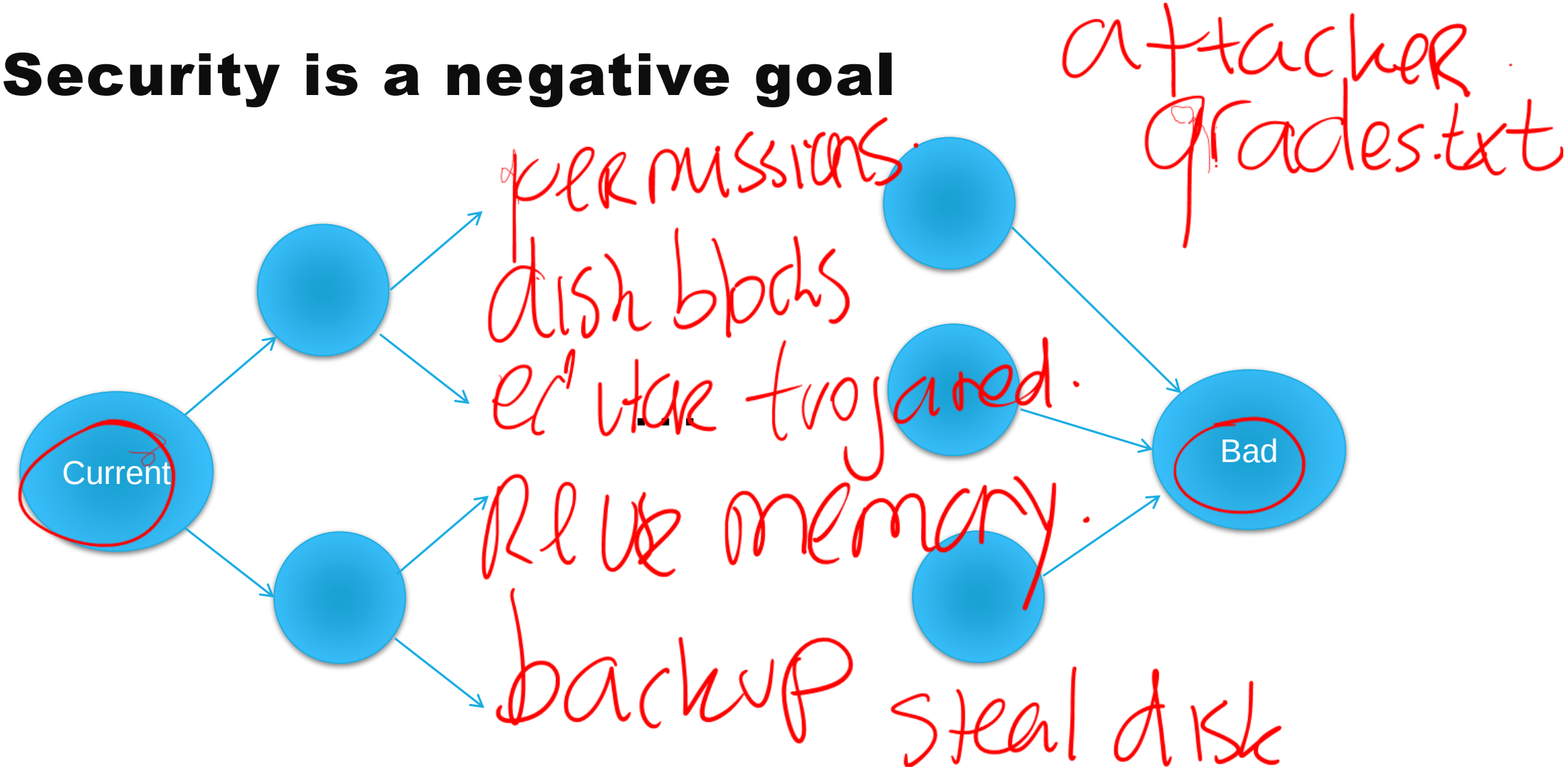
Security is a negative goal



Many ways for an attacker to break system

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Difficult to achieve negative goals

The designer must protect against *all* possible ways that attacker can break system

The designer is likely to miss one path

How to mitigate problems?

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This session: three big ideas

1. Complete mediation
2. Privilege separation
3. Minimize trusted computing base

This is difficult; bugs are in unexpected places

Case study: undefined behavior bugs

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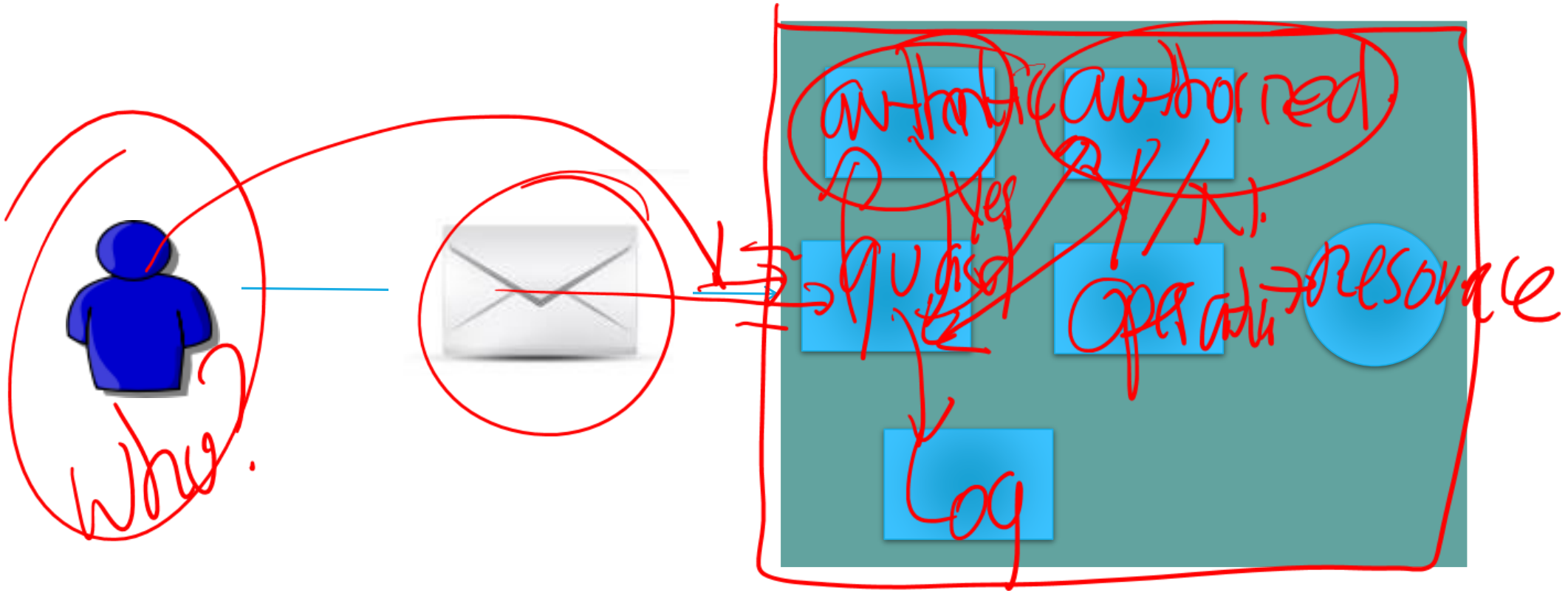
Complete mediation w. guard model



Computer system

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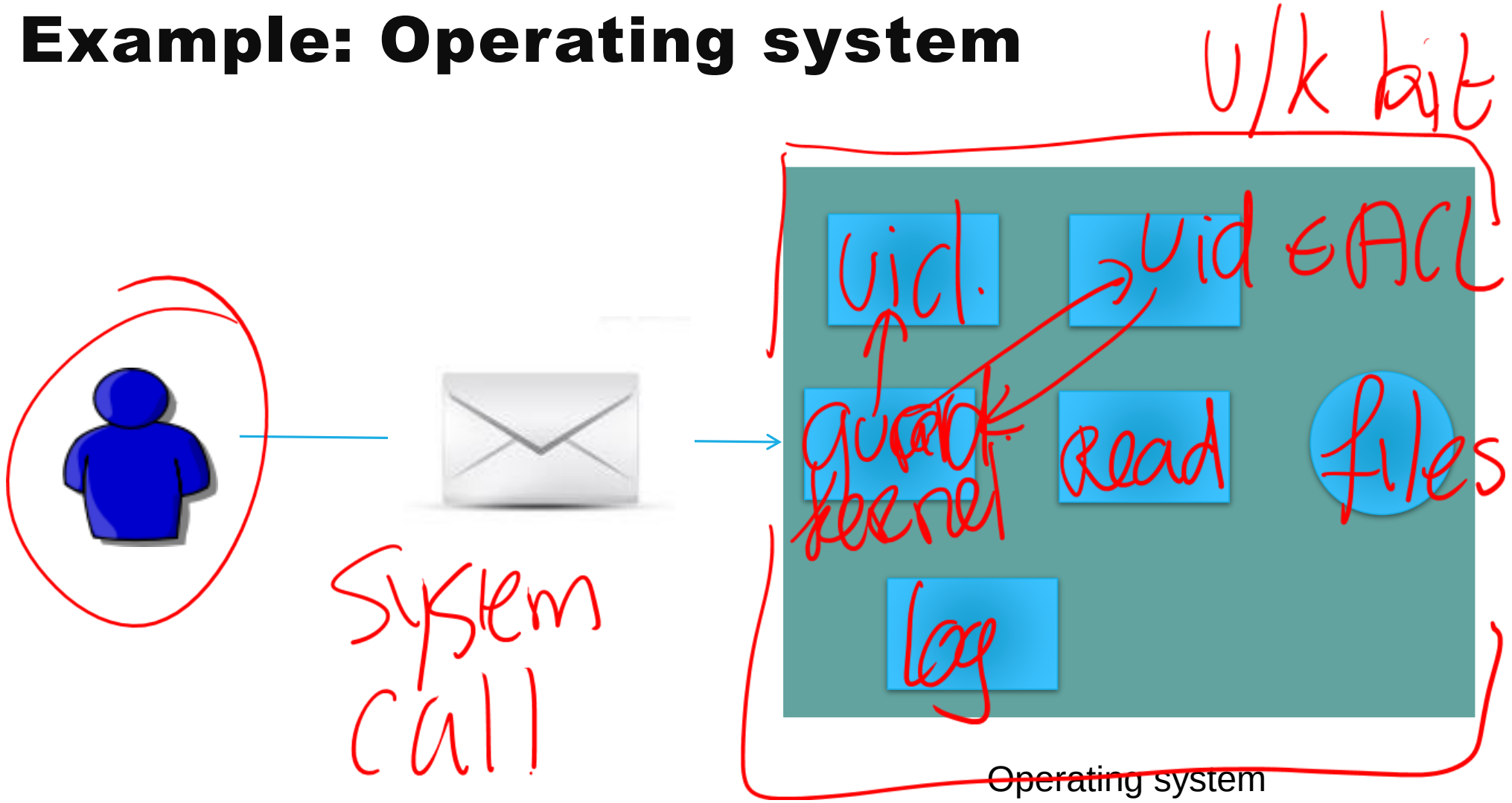
Example: Operating system



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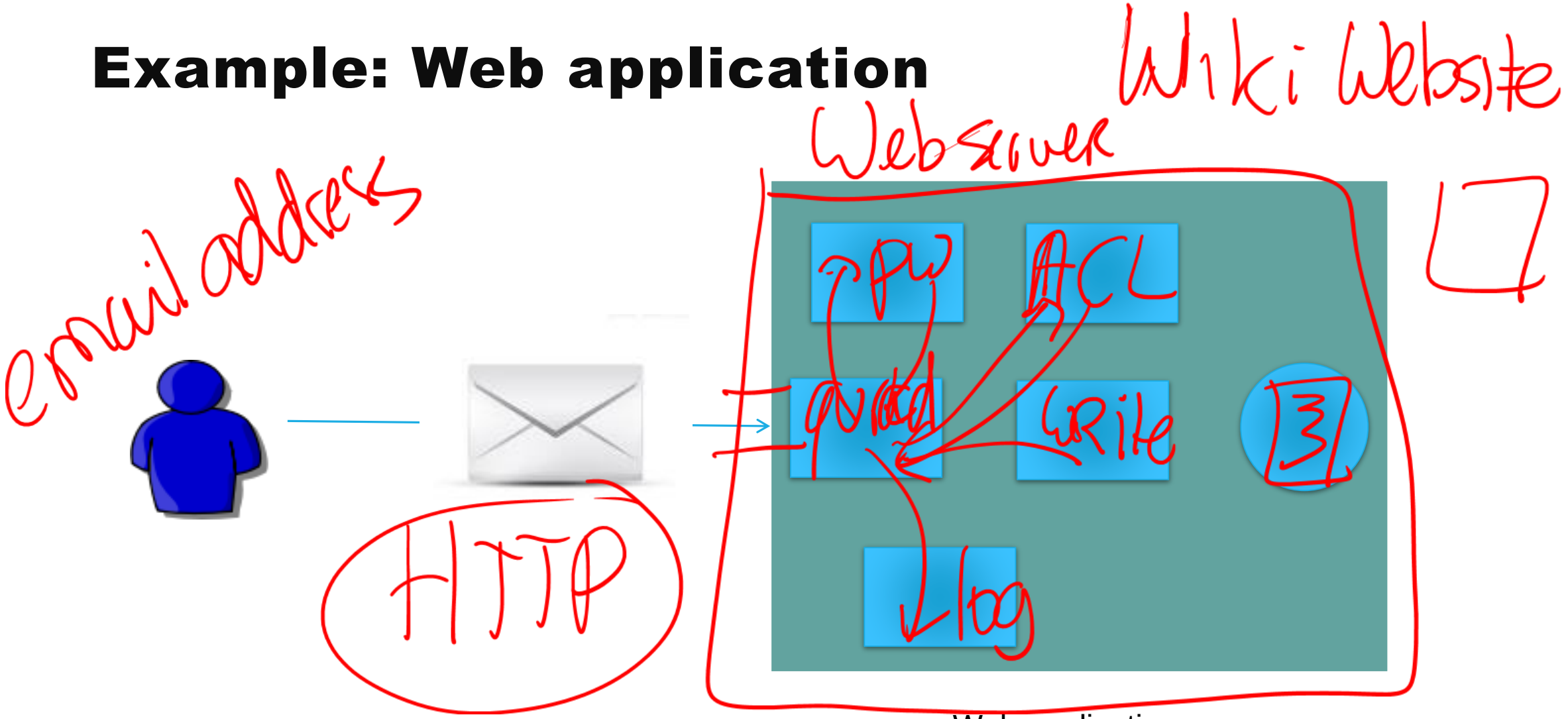
Example: Web application



Web application

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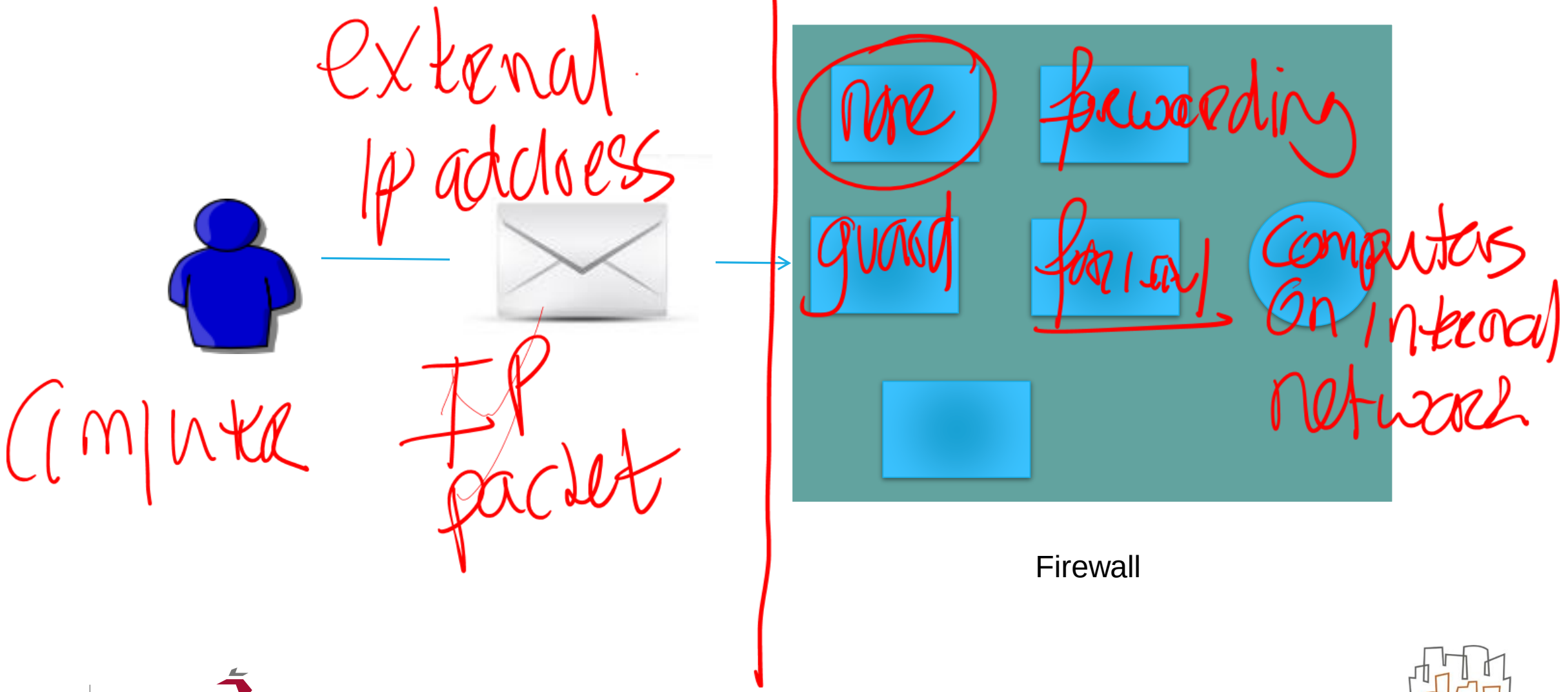
Example: firewall



Firewall

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Model is simple. What can go wrong?

Complete mediation is challenging

- All ways to access must be checked; backdoors?

Software bugs in mediation

- One bug per ~1,000 lines of code

Mismatch between policy and mechanism

- What should the firewall rules be?

Policy is challenging to get right

- Example: security questions are easier to guess than password
- No way to enforce “Only if user forgets password, then …”

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Summary so far

Guard model is good, but hard to get right

Any principled ideas to improve further?

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Separation of privilege

Split system into modules and give each module the *least* privilege to do its job

Examples:

1. Use several physical machines: run database on different machine than web site
2. Use virtual machines to split
3. Split applications in components

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Example: bad design shopping web site

Design:

- Requests: product searches, take orders
- Store product info and orders in same DB

Bad properties:

- Bug in search software (e.g., SQL injection) can expose credit card numbers
- *All* software is *trusted*

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Example: better design shopping web site

Idea: reduce trusted code

Two servers:

1. One server doing search
2. One server doing orders

Good properties:

- If no interaction between servers, search cannot obtain credit card numbers
- Search software is now *untrusted*.

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Challenges in privilege separation

1. Modules need to share
   Search software may need access to orders database
2. Need system support
   Must be able to compartmentalize servers
   Support controlled sharing
3. Need to configure privileges carefully
   Give servers privileges for accessing only their DB
4. Performance
   Two servers maybe less efficient than 1
5. Reduce trusted software

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Trust computing base (TCB)

All software that must be trusted to achieve security

Big goal in security: *reduce* TCBs

less software ➔fewer bugs ➔fewer exploits

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Challenge: bug-free TCB

Bug in TCB undermines privilege separation

TCB are often large and complex (e.g., kernel)

- Large *and* complex ➔ bugs
- Many types of bugs

New classes of bugs are discovered

- Case study: undefined behavior [SOSP 2013]

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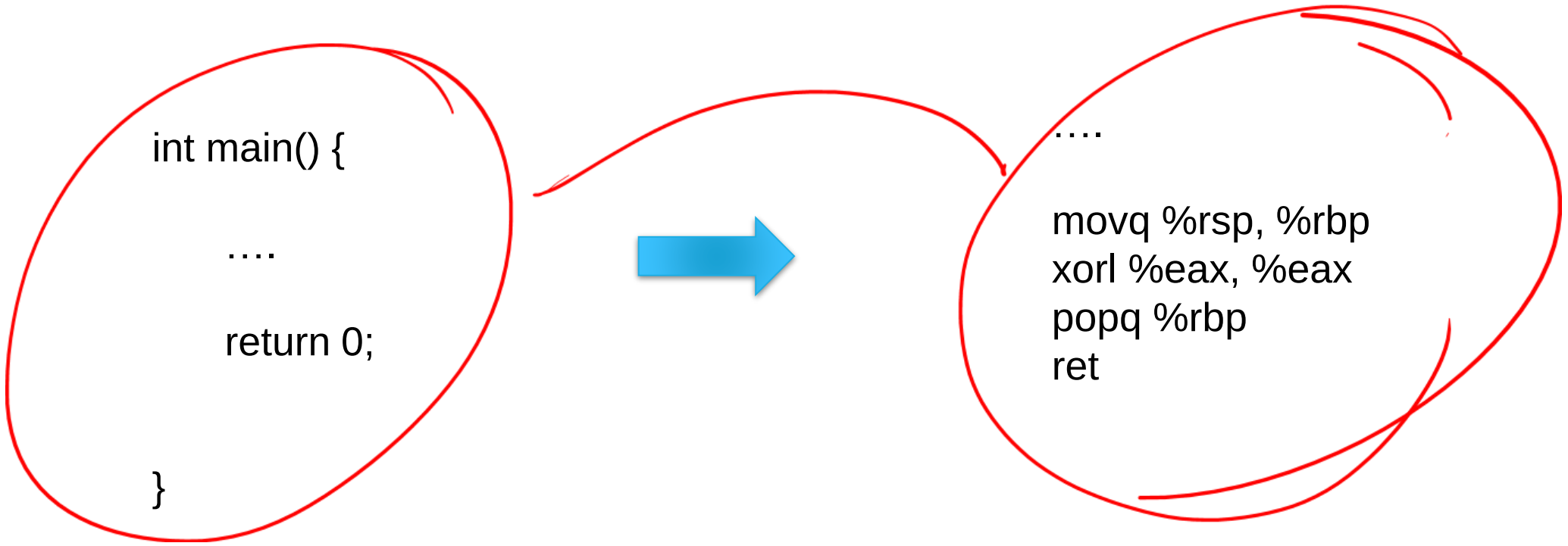
Belief: compiler is faithful translator



Not true if code invokes undefined behavior

This has bad security implications

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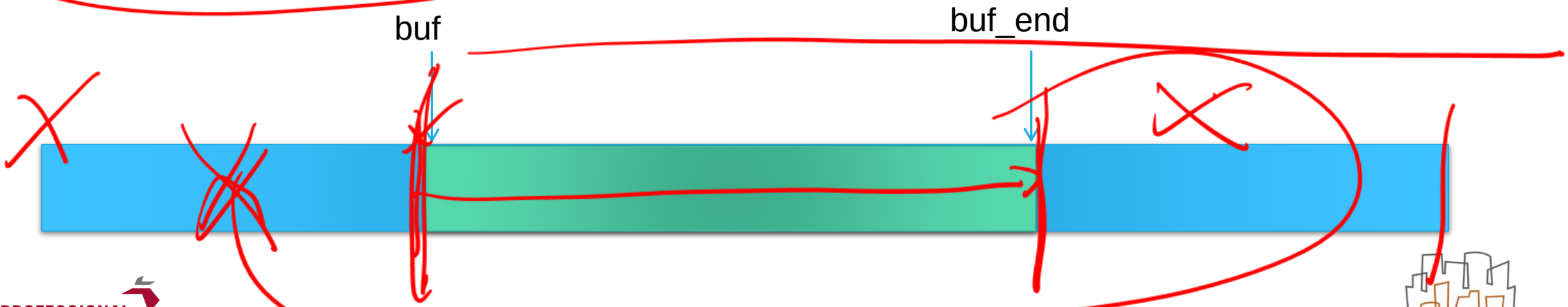
Example: compiler discards sanity check

```
char *buf = …;
char *buf_end = …;
unsigned int off = /* supplied by untrusted source */
if (buf + off >= buf_end)
    return;
if (buf + off < buf)
    return;
/* access buf[0..off-1] */
```

Linux kernel
Chrome
Python interpreter



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Undefined behavior allows such optimziations

Undefined behavior: the spec "imposes no requirements"

E.g., pointer overflow (buf+off)

Original goal: emit efficient code

E.g., no bounds checks emitted. Good on hardware that does bounce checking in hardware.

Now compilers optimize code with undefined behavior away.

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Examples of undefined behavior in C

Meaningless checks from real code:

Pointer overflow:	if (p + 100 < p)
Signed integer overflow:	if (x + 100 < x)
Oversized shift:	if (!(1 << x))
Null pointer dereference:	*p; if (p)
Absolute value overflow:	if (abs(x) < 0)

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Unstable code confuses programmers

Unstable code: compilers discard code due to undefined behavior

Compiler writers assume programmer *never* invokes undefined behavior. If there is undefined behavior, programmer could not have intended it. So, it is ok to optimize it away.

Unfortunately, programmers don't know the exact semantics of C, and read write code with undefined behavior without realizing it.

Effects:

- Security checks discarded
- Weakness amplified
- Unpredictable system behavior

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Unstable code confuses programmers

"This optimization will create MAJOR SECURITY ISSUES in ALL MANNER OF CODE. I don't care if your language lawyers tell you gcc is right …. FIX THIS! NOW!"

A gcc user

Bug #30475 assert(int + 100> int) optimized away

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Response from gcc developers

"I am sorry that you wrote broken code to begin with … GCC is not going to change."

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Test existing compilers

12 C/C++ compilers

- gcc
- aCC (HP)
- icc (Intel)
- open64 (AMD)
- suncc (Oracle)
- ti (TMS320C6000)
- clang
- armcc (ARM)
- msvc (Microsoft)
- pathcc (PathScale)
- xlc (IBM)
- windriver (Diab)

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Compilers often discard unstable code

	`if` $(p + 100 < p)$	$*p$; `if` $(!p)$	`if` $(x + 100 < x)$	`if` $(x^+ + 100 < 0)$	`if` $(!(1 << x))$	`if` $(\text{abs}(x) < 0)$
gcc-2.95.3	–	–	O1	–	–	–
gcc-3.4.6	–	O2	O1	–	–	–
gcc-4.2.1	O0	–	O2	–	–	O2
gcc-4.8.1	O2	O2	O2	O2	–	O2
clang-1.0	O1	–	–	–	–	–
clang-3.3	O1	–	O1	–	O1	–
aCC-6.25	–	–	–	–	–	O3
armcc-5.02	–	–	O2	–	–	–
icc-14.0.0	–	O2	O1	O2	–	–
msvc-11.0	–	O1	–	–	–	–
open64-4.5.2	O1	–	O2	–	–	O2
pathcc-1.0.0	O1	–	O2	–	–	O2
suncc-5.12	–	O3	–	–	–	–
ti-7.4.2	O0	–	O0	O2	–	–
windriver-5.9.2	–	–	O0	–	–	–
xlc-12.1	O3	–	–	–	–	–

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Observations

Compilers silently remove unstable code

Compilers have become more aggressive over time

Different compilers behave differently

Change/upgrade compiler ➔ broken system

➔Need a systematic approach

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Our approach: precisely flag unstable code

C/C++ source ➔ LLVM IR ➔

STACK ➔ warnings

```
% ./configure
% stack-build make    # intercept cc
% poptck                    # run STACK
```


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Design overview of STACK

What's the difference, compilers vs most programmers?

- Assumption Δ: programs don't invoke undefined behavior

What can compilers do only with assumption Δ?

- Optimize away unstable code

Stack: mimic a compiler that selectively enables Δ

- Phase 1: optimize without Δ
- Phase 2: optimize with Δ
- Unstable code: differences between the two phases

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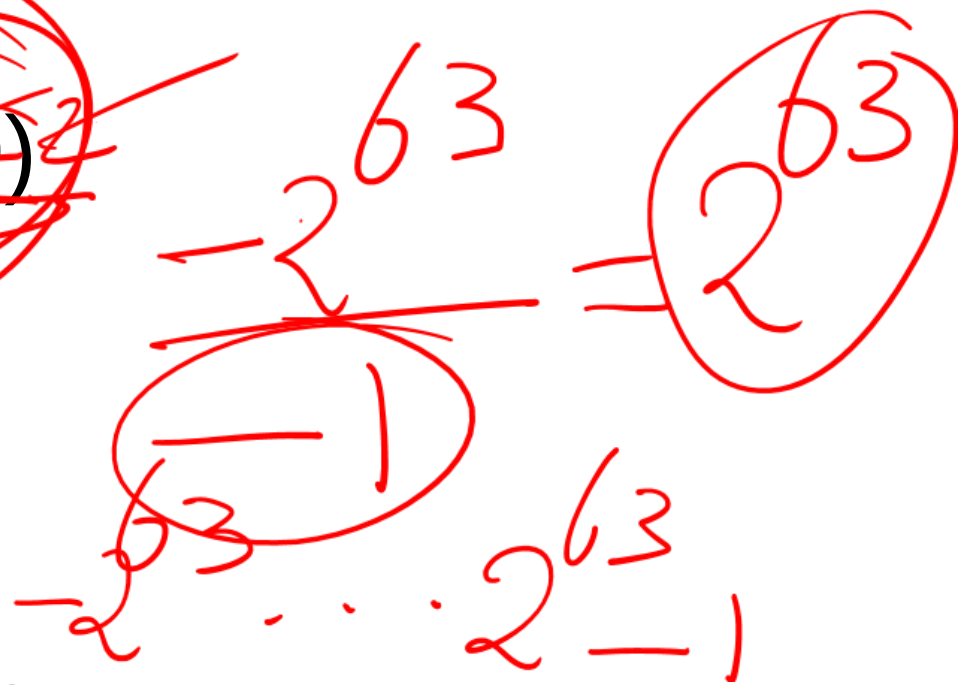
Example of identifying unstable code

1. res = x/y;
2. if (y == -1 && x < 0 && res < 0)
3. return; /* $-2^{63}/-1 < 0$ */



Assumption:

No division by zero: y ≠ 0

No division overflow: y ≠ -1 or x ≠ INT_MIN

STACK can optimize “res < 0” to false only with Δ

Phase 1: is res < 0 = false in general? No

Phase 2: is res < 0 = false with Δ? Yes.

Report res < 0 as unstable code.

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STACK finds new bugs

Applied STACK to many popular systems

Inspected warnings and submitted patches to developers

Binutils, Bionic, Dune, e2fsprogs, Ffmpeg+Libav, file, FreeType, GMP, GRUB, HiStar, Kerberos, libX11, libarchive, libgcrypt, Linux kernel, Mosh, Mozilla, OpenAFS, OpenSSH, OpenSSL, PHP, plan9port, Postgres, Python, QEMU, Ruby+Rubinius, Sane, uClibc, VLC, Wireshark, Xen, Xpdf

Developers accepted most of our patches

160 new bugs

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STACK warnings are precise

Kerberos: STACK produced 11 warnings

Developers accepted every patch
No warnings for fixed code
Low false warning rate: 0/11

Postgres: STACK produced 68 warnings

9 patches accepted: server crash
29 patches in discussion: developers blame compilers
26 time bombs: can be optimized away by future compilers
4 false warnings: benign redundant code
Low false warning rate: 4/68

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Unstable code is prevalent

Applied STACK to all Debian Wheezy packages

- 8,575 C/C++ packages
- ~150 days of CPU time to build and analyze

STACK warns in ~40% of C/C++ packages

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How to avoid unstable code

Programmers

Fix bugs

Workaround: disable certain optimizations

Compilers & checkers

Many bug-finding tools fail to model C spec correctly

Use our ideas to generate better warnings

Language designers: revise the spec

Eliminate undefined behavior? Perf impact?

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Stepping back: how to avoid bugs

Bugs are the source of many security vulnerabilities

Compartmentalize bugs using privilege separation

Minimize TCB

Next session will talk about approaches to eliminate certain kinds of bugs

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THANK YOU

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