Divergent Representations:
When Compiler Optimizations Enable Exploitation

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Divergent Representations: Key Takeaways

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Common: 45% of scanned projects.
Divergent Representation: Definition

A source code variable compiled so that some of its uses have different semantic representations.
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Clang14 -O1

```assembly
mov eax, -1;
lea rcx, [rdi + 1];
cmp byte ptr [rdi], sil;
mov rdi, rcx;
jne
ret;
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32-bit

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int i;
for (i=0; buf[i] != ch; i++) {}  
return i;
```

If `i` overflows: divergent values

```
Clang14 -O1

mov eax, -1;
add eax, 1;
lea rcx, [rdi + 1];
cmp byte ptr [rdi], sil;
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compiler optimizations + undefined behavior = unexpected vulnerabilities

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\[
\text{if (buf + i < buf)}
\]
\[
\quad \text{return;}
\]
\[
\text{buf[i] = '0';}
\]

\[
\text{struct tun_struct *tun = ...;}
\]
\[
\text{struct sock *sk = tun->sk;}
\]
\[
\text{if (!tun)}
\]
\[
\quad \text{return POLLERR;}
\]

Previous work [1,2] showed:

compiler optimizations + undefined behavior = unexpected vulnerabilities

if (buf + i < buf)
    return;
buf[i] = '\0';

struct tun_struct *tun = ...;
struct sock *sk = tun->sk;
if (!tun)
    return POLLERR;

True iff undefined behavior occurs.

Previous work [1,2] showed:

compiler optimizations + undefined behavior = unexpected vulnerabilities

if (buf + i < buf) return;
buf[i] = ‘\0’;

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This work: benign patterns in compiled code to exploit existing vulnerabilities.
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Similar to ROP gadgets.
Case Study: SQLite CVE-2022-35737

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Exploit: overwrite saved return address and return.
  - Requires precise data conditions.

Conditions only satisfiable because of a divergent representation.
Case Study: SQLite divrep helps exploit buffer overflow

```c
int len, nspecial;
char output[BUF_SIZE];

for (i=0; input[len] != '\0'; len++) {
    if (input[len] == quote) nquotes++;
    while (unicode_prefix(input[len])) len++;
}

if (len + nquotes <= BUF_SIZE)
    memcpy_and_escape(output, input, len);
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1. **Scan** input string: count quotes and total number of bytes.

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Exploit conditions:
- \texttt{len + nquotes} must overflow
- \texttt{len} must be small during memcpys

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Exploit conditions:

- `len + nquotes` must overflow
- `len` must be small during memcpy

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Problem: len < nquotes → len must overflow → negative memory index.

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Key insight: increment \( len \) with different semantics to meet conditions.

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32-bit
64-bit

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E.g., avoid negative memory offsets by using unicode characters to increment \( len \) with 64-bit semantics whenever a 32-bit value is undesirable.

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if (len + nquotes <= BUF_SIZE)
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32-bit

64-bit

input
```
\[0x7FFFFFFF\]
```

0x7FFFFFFF

33
Case Study: SQLite divrep helps exploit buffer overflow

*Canaries not considered.*
Divergent Representations: How common are they?
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Source code search - C/C++

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Binary code search

Binary Ninja plugins to identify instances of different register sizes and semantics for same variable.
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Binary Ninja plugins to identify instances of different register sizes and semantics for same variable.

Counts are under-approximations: other forms of divergent representations may exist.
Distribution of Source Code Divergent Representation Candidates

Number of repositories

No. of div. rep. candidates found in a repository (inclusive)
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Number of repositories

0  1 - 9  10 - 99  100 - 199  200+

554  329  102  12  2

45%
Distribution of Source Code Divergent Representation Candidates

- 554 repositories with 0 divergent representation candidates.
- 329 repositories with 1 to 9 divergent representation candidates.
- 102 repositories with 10 to 99 divergent representation candidates.
- 12 repositories with 100 to 199 divergent representation candidates.
- 2 repositories with 200+ divergent representation candidates.

45% of repositories have divergent representation candidates.
<table>
<thead>
<tr>
<th>Optimization Level</th>
<th>Clang</th>
<th>GCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>-O0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-O1</td>
<td>23</td>
<td>33</td>
</tr>
<tr>
<td>-O2</td>
<td>26</td>
<td>37</td>
</tr>
<tr>
<td>-O3</td>
<td>30</td>
<td>53</td>
</tr>
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```c
int i;
for (i=0; buf[i] != ch; i++) {} return i;
```

```c
size_t i;
for (i=0; buf[i] != ch; i++) {} return i;
```
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Our tools should reason about divergent representations:

- Source code: linters
- Binary: decompilers

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Benign in isolation, but dangerous with a vulnerability.

- Must understand causes and risks.
- Ought to prevent when acceptable.