UNDER-CONSTRAINED SYMBOLIC EXECUTION: CORRECTNESS CHECKING FOR REAL CODE

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CONTRIBUTIONS

- Technique + tool for finding deep bugs in **real**, open source C/C++ code
  - No manual testcases
  - No functional specification
- Bugs reported **may** have security implications; exploitability must be determined manually
  - Memory access, heap management, assertion failures, division-by-zero
- Found 77 new bugs in BIND, OpenSSL, Linux kernel
  - 2 OpenSSL DoS vulnerabilities: CVE-2014-0198, CVE-2015-0292
  - 14 Linux kernel vulnerabilities (mostly minor DoS issues)

MOTIVATION: CURRENT PRACTICE

- Code reviews
- "Safer" languages
- Manual (regression) testing
- Static analysis (Coverity, clang static analyzer, etc.)

Bugs are everywhere!

SYMBOLIC EXECUTION

- Provide *symbolic* rather than *concrete* inputs
- Conceptually: explore **all** paths through a program
- Accurately track all memory values (bit precision)
- Report paths/inputs that crash
  - Generate concrete testcase
- KLEE tool (prior work: OSDI 2008)

EXAMPLE

`x` is **symbolic** input

```
int foo(int x) {
  if (x)
    return x/10;
  else
    return 10/x;
}
```

EXAMPLE

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  if (x)
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  else
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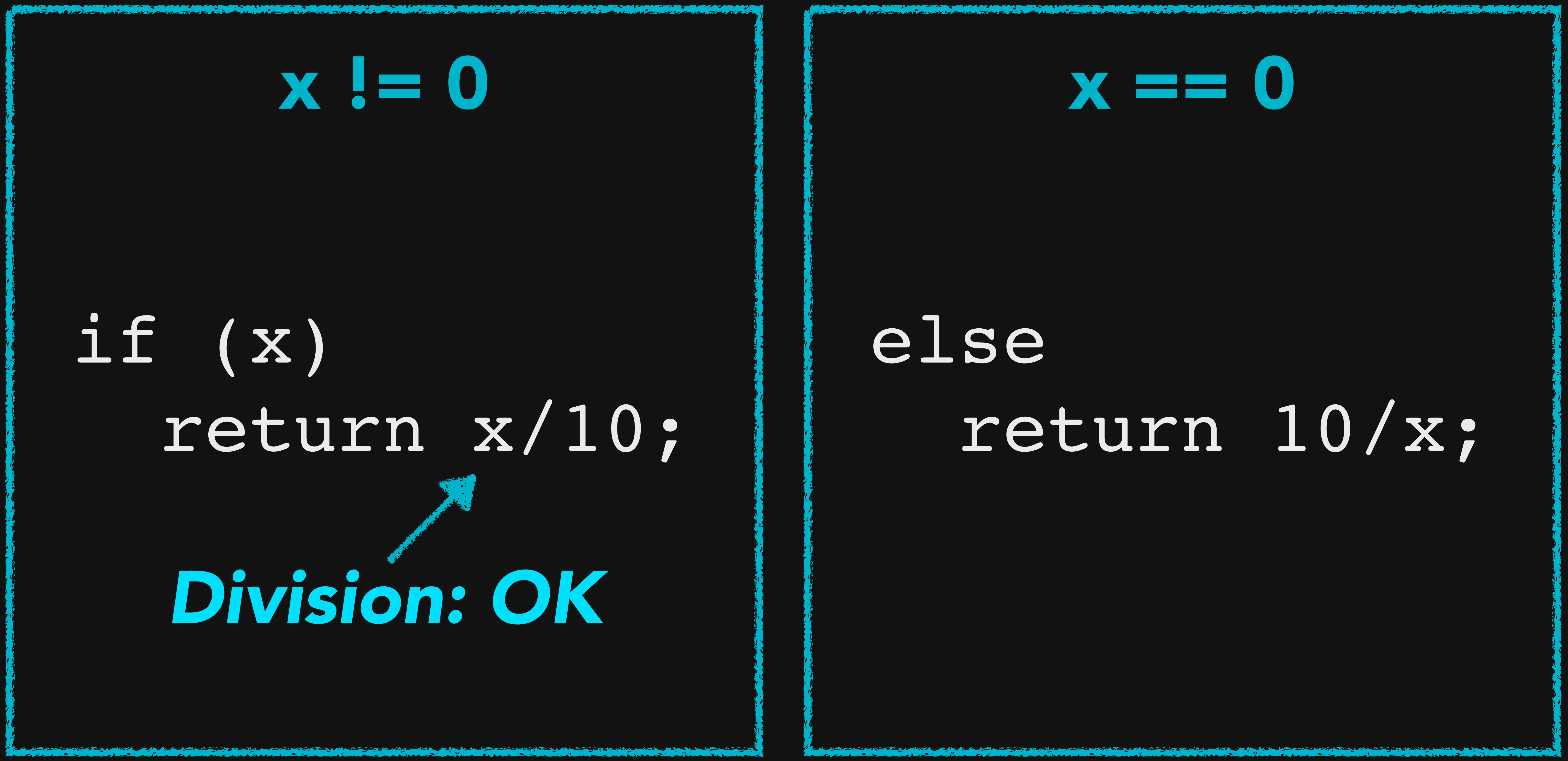
}
```

symbolic branch

EXAMPLE



x != 0

```
if (x)
   return x/10;
```

Division: OK

State 1

x == 0

```
else
   return 10/x;
```

State 2

EXAMPLE

Division: ERROR

PROBLEM: SCALABILITY

- Path explosion
  - $|\text{paths}| \sim 2^{|\text{if-statements}|}$
- Path length and complexity
  - Undecidable: infinite-length paths (halting problem)
- SMT query complexity (NP-complete)

SOLUTION: UNDER-CONSTRAINED

- Directly execute individual functions within a program
  - Less code = Fewer paths
  - Function calls executed (inter-procedural)
  - Able to test previously-unreachable code
- Challenges
  - **Complex inputs** (e.g., pointer-rich data structures)
  - Under-**constrained**: inputs have unknown preconditions
    - False positives

UC-KLEE TOOL

- Extends KLEE tool (OSDI 2008)
- Runs LLVM bitcode compiled from C/C++ source
- Automatically synthesizes complex inputs
    - Based on *lazy initialization* (Java PathFinder)
    - Supports pointer manipulation and casting in C/C++ (no type safety)
    - User-specified input depth (*k*-bound) [Deng 2006]

LAZY INITIALIZATION

- Symbolic (input) pointers initially **unbound**
- On first dereference:
  - New object allocated
  - Symbolic pointer **bound** to new object's address
  - Assume no aliasing (i.e., no cyclical data structures)
- On subsequent dereferences:
  - Pointer resolves to object allocated above

EXAMPLE

unbound symbolic input

```
int listSum(node *n) {
  int sum = 0;
  while (n) {
    sum += n->val;
    n = n->next;
  }
  return sum;
}
```

EXAMPLE

```
int listSum(node *n) {
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  }
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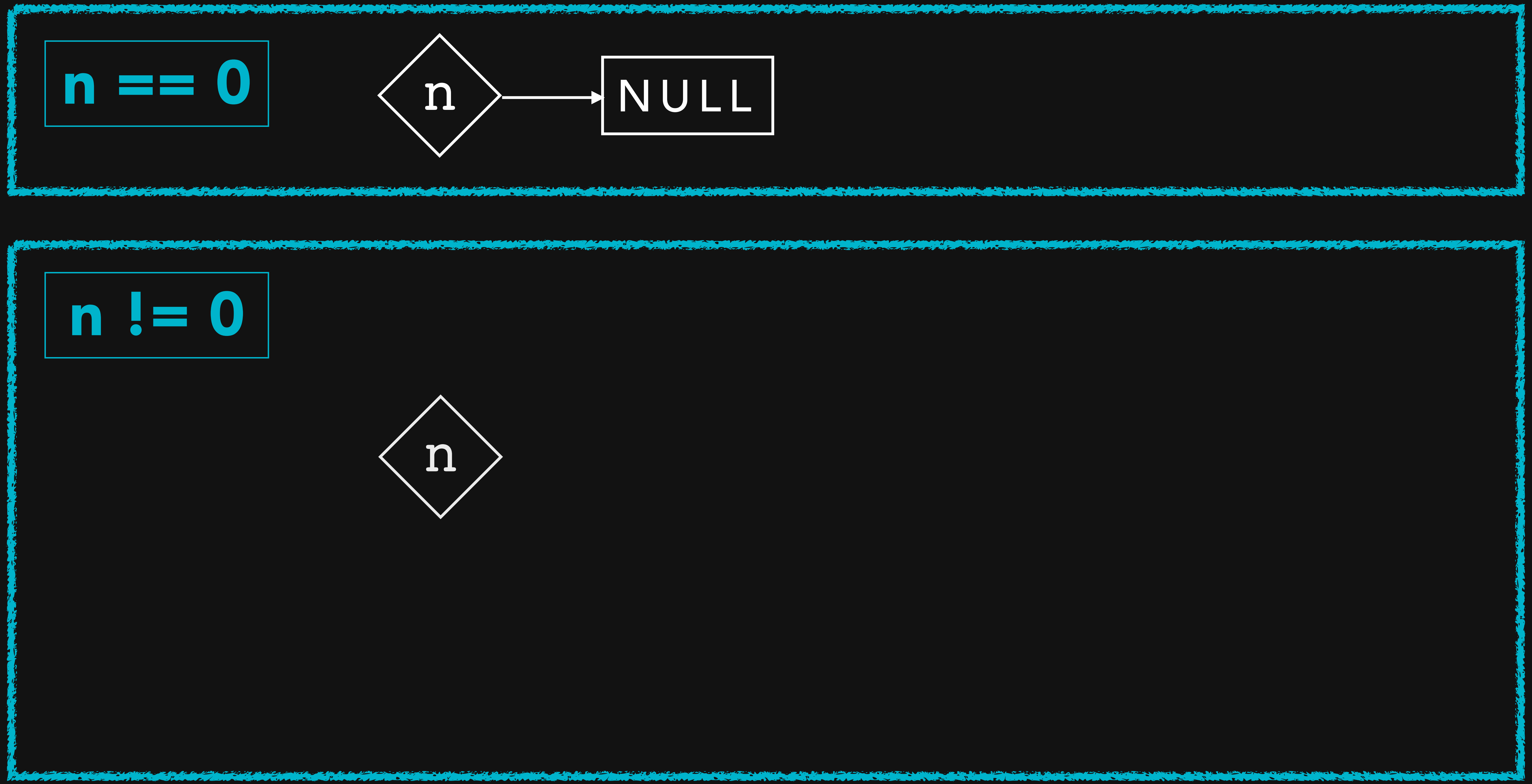

EXAMPLE

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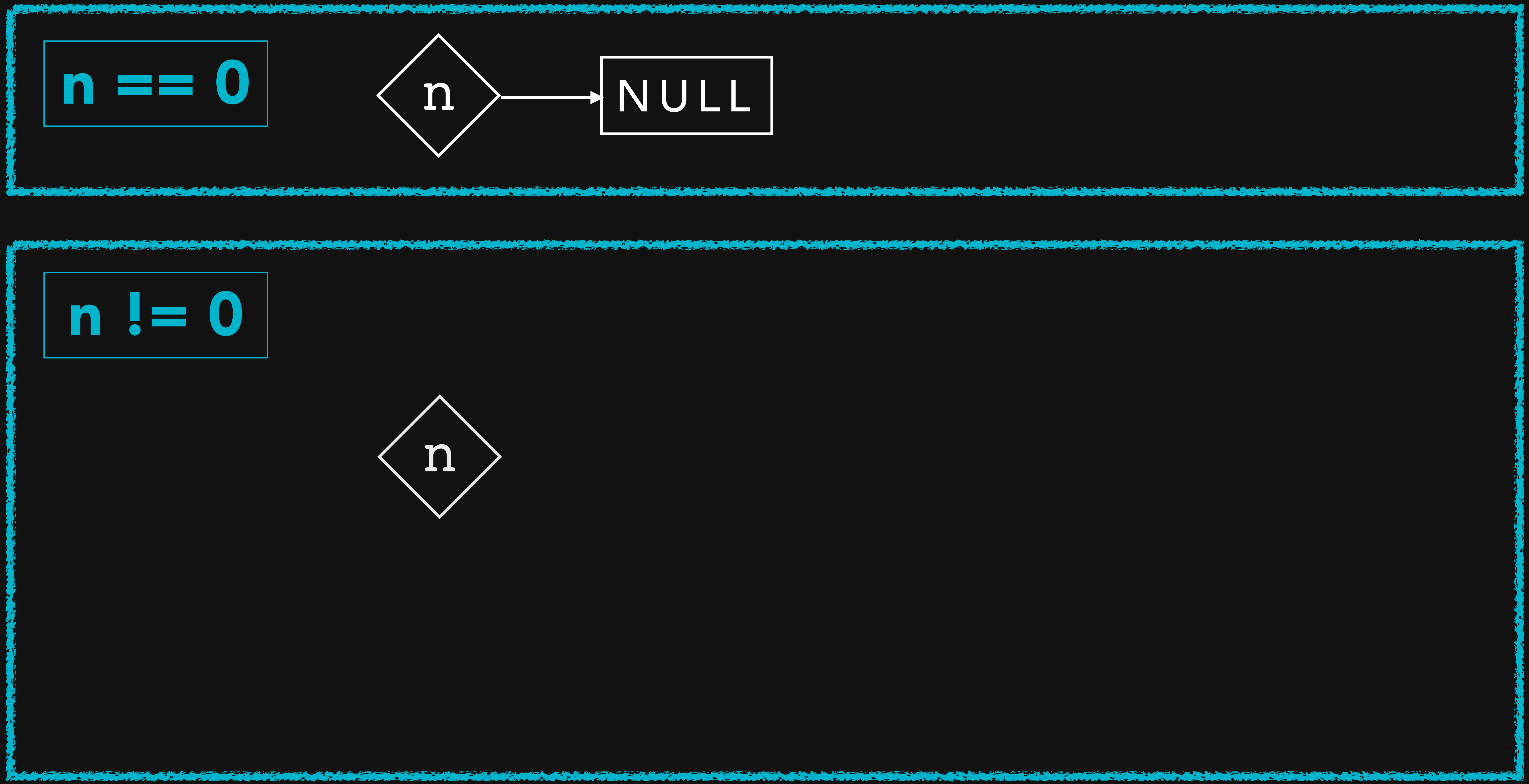

n == 0

n != 0

EXAMPLE

```
int listSum(node *n) {
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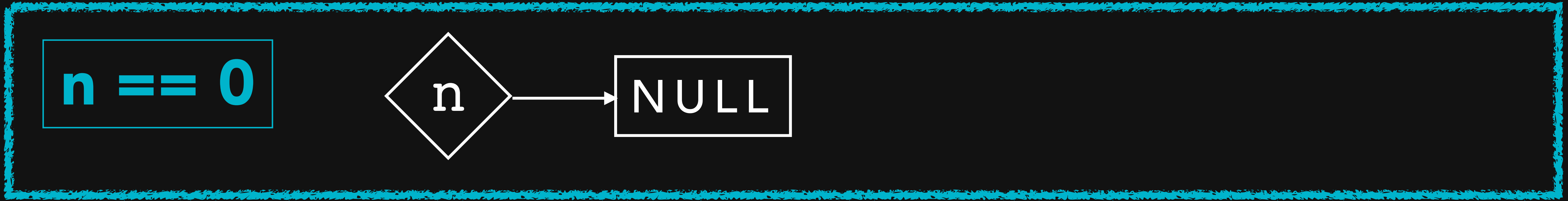

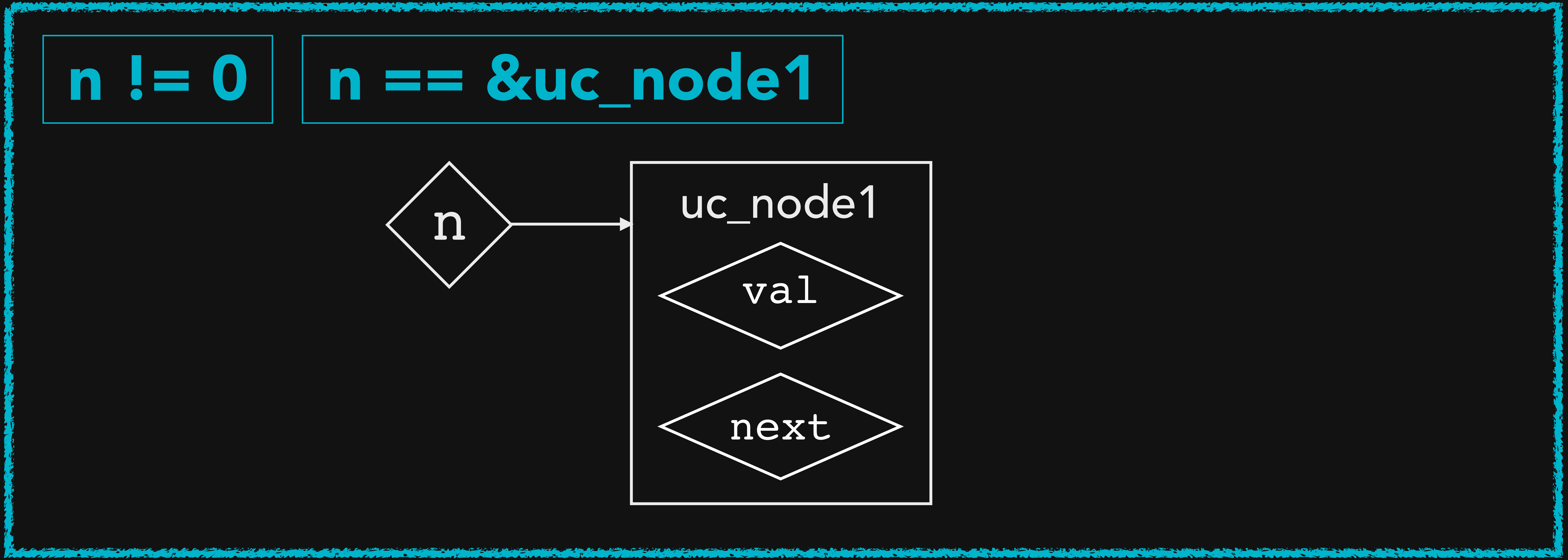

EXAMPLE

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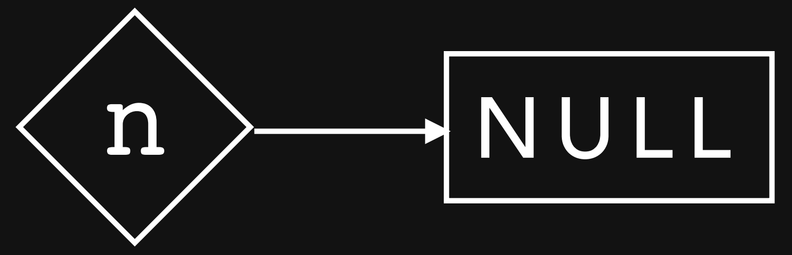
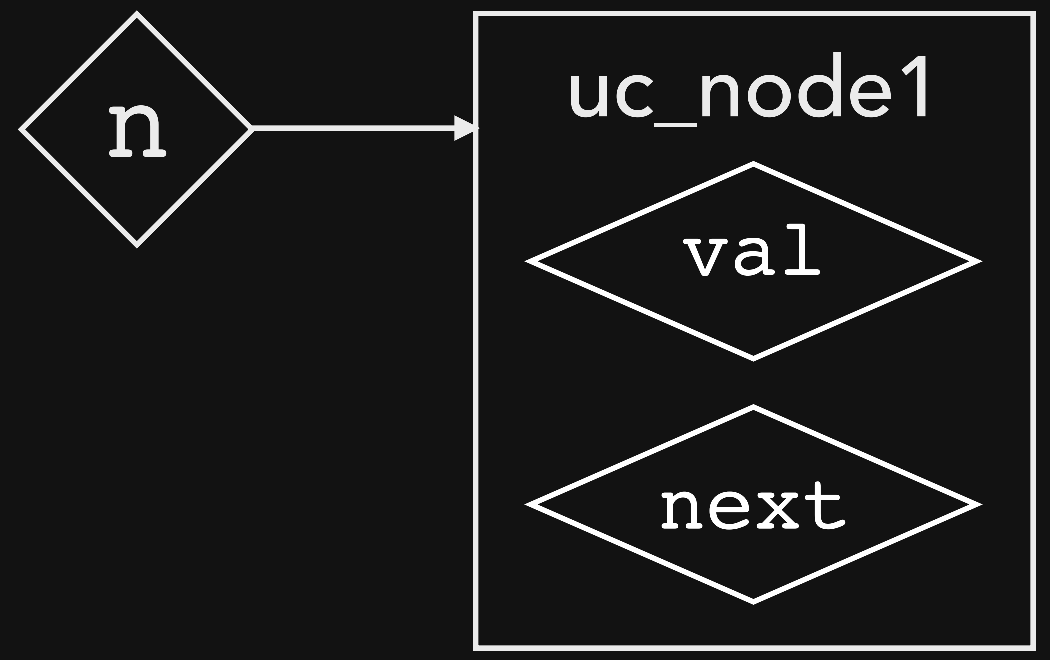


n != 0

n == &uc_node1



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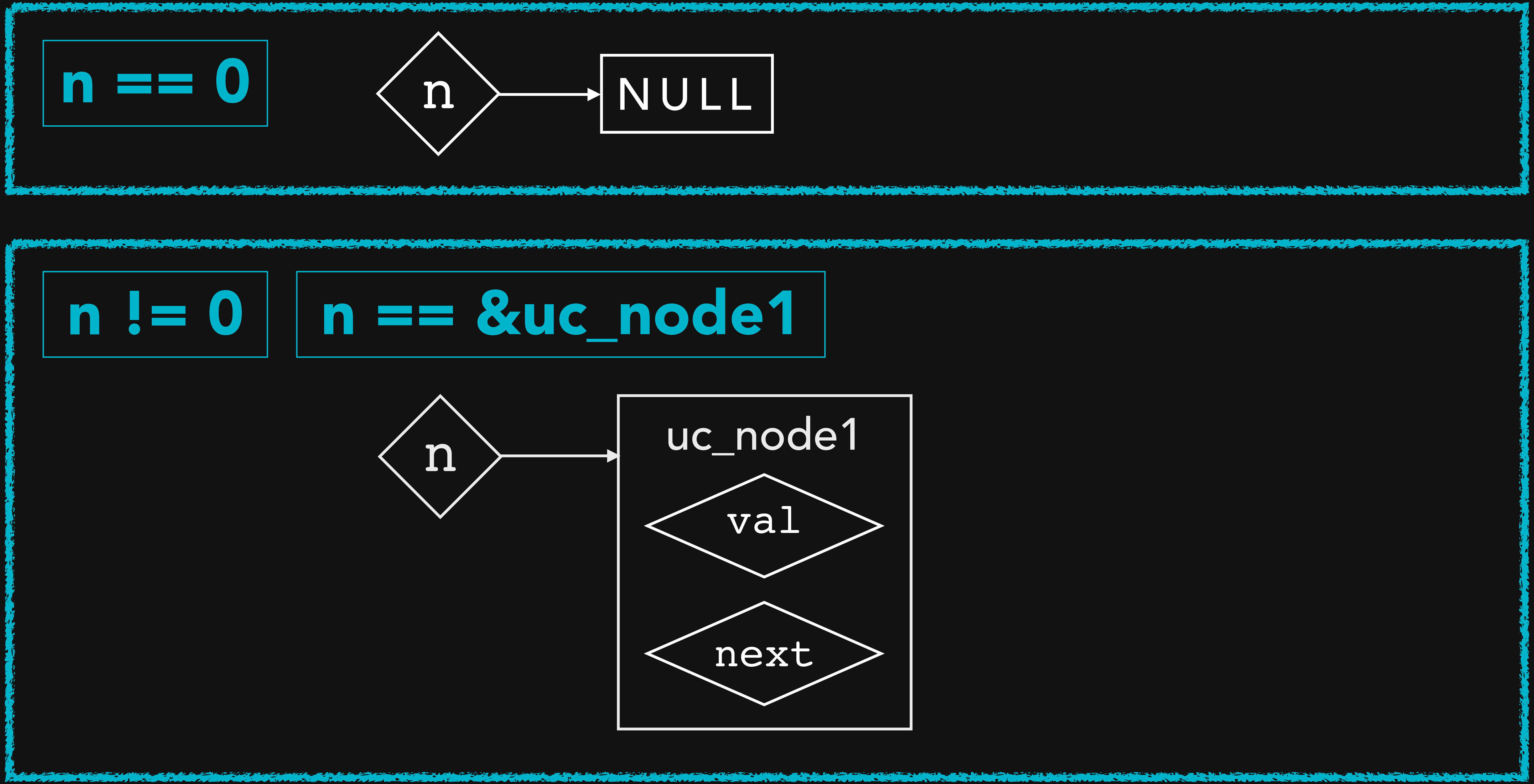

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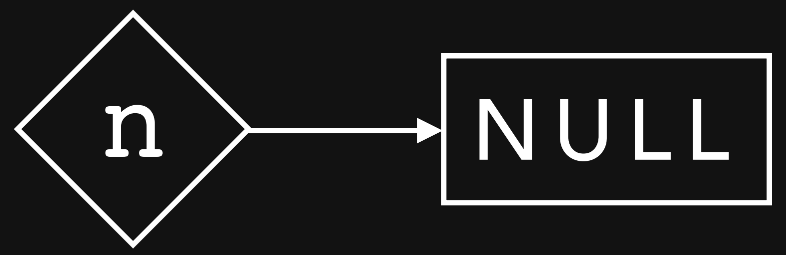
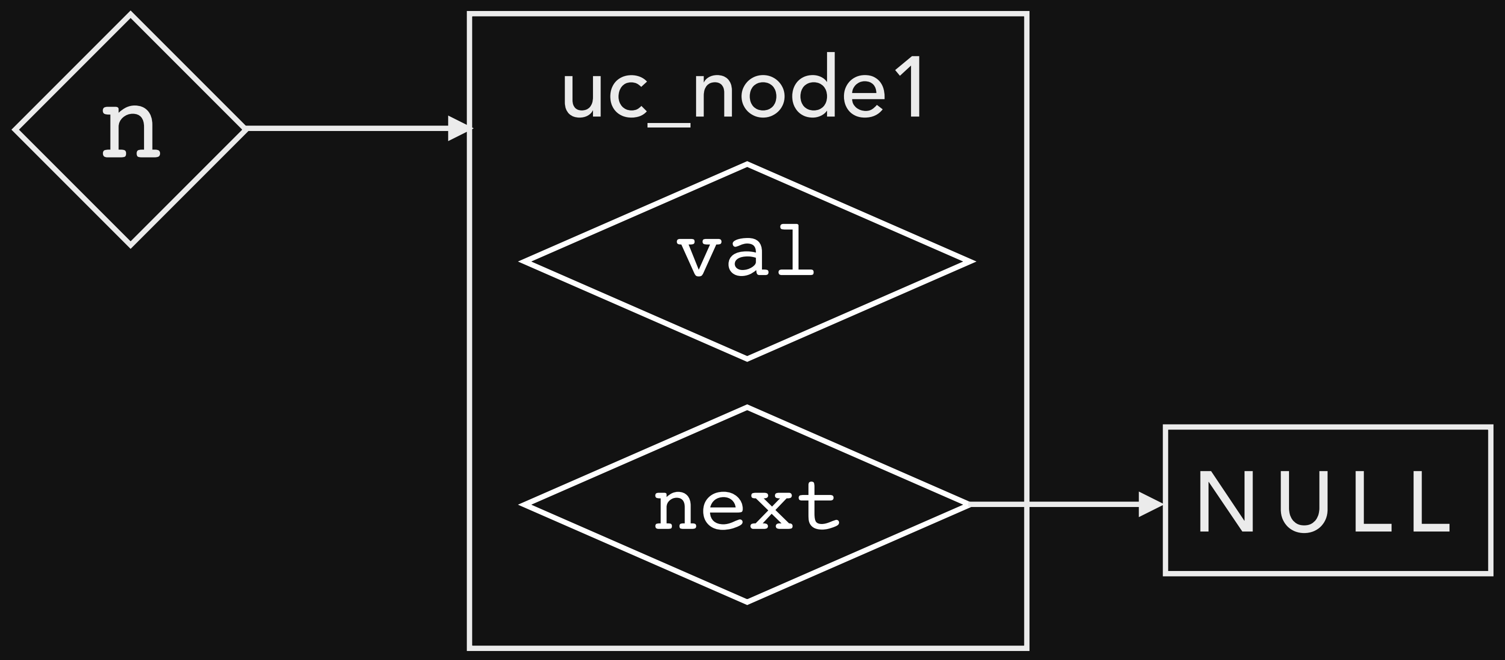


n != 0 **n == &uc_node1** **uc_node1.next == 0**



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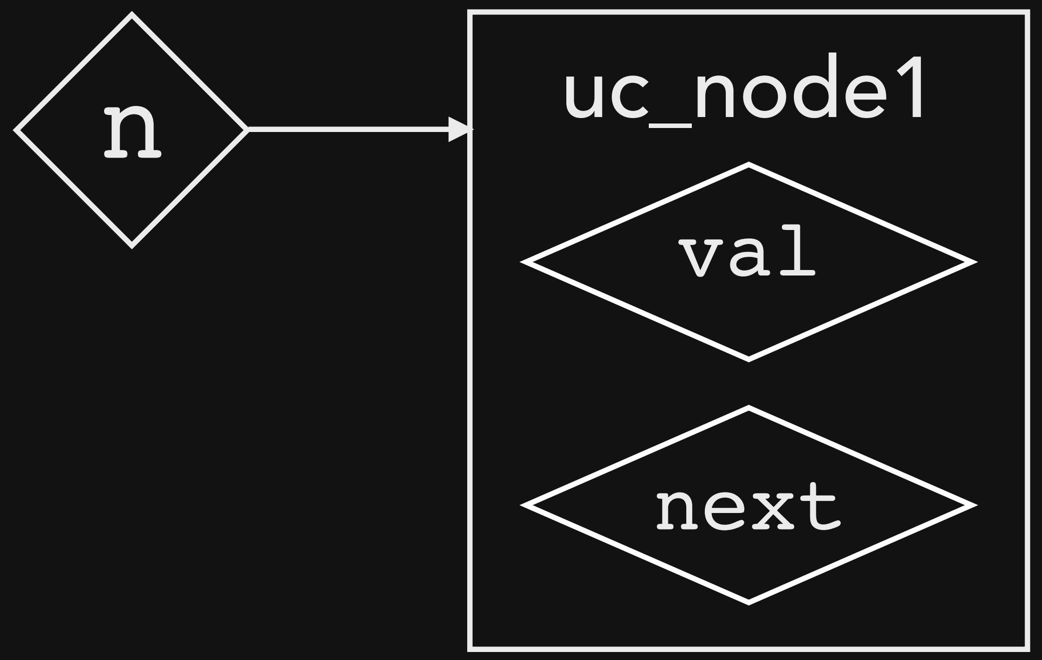

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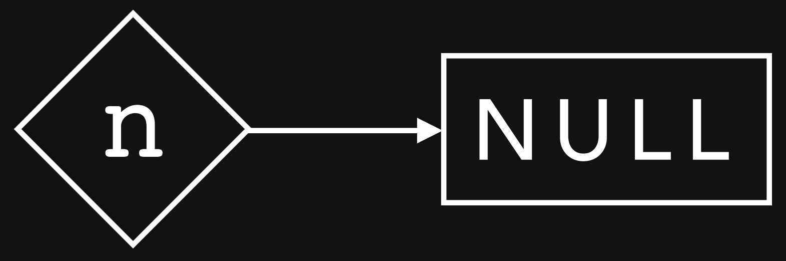

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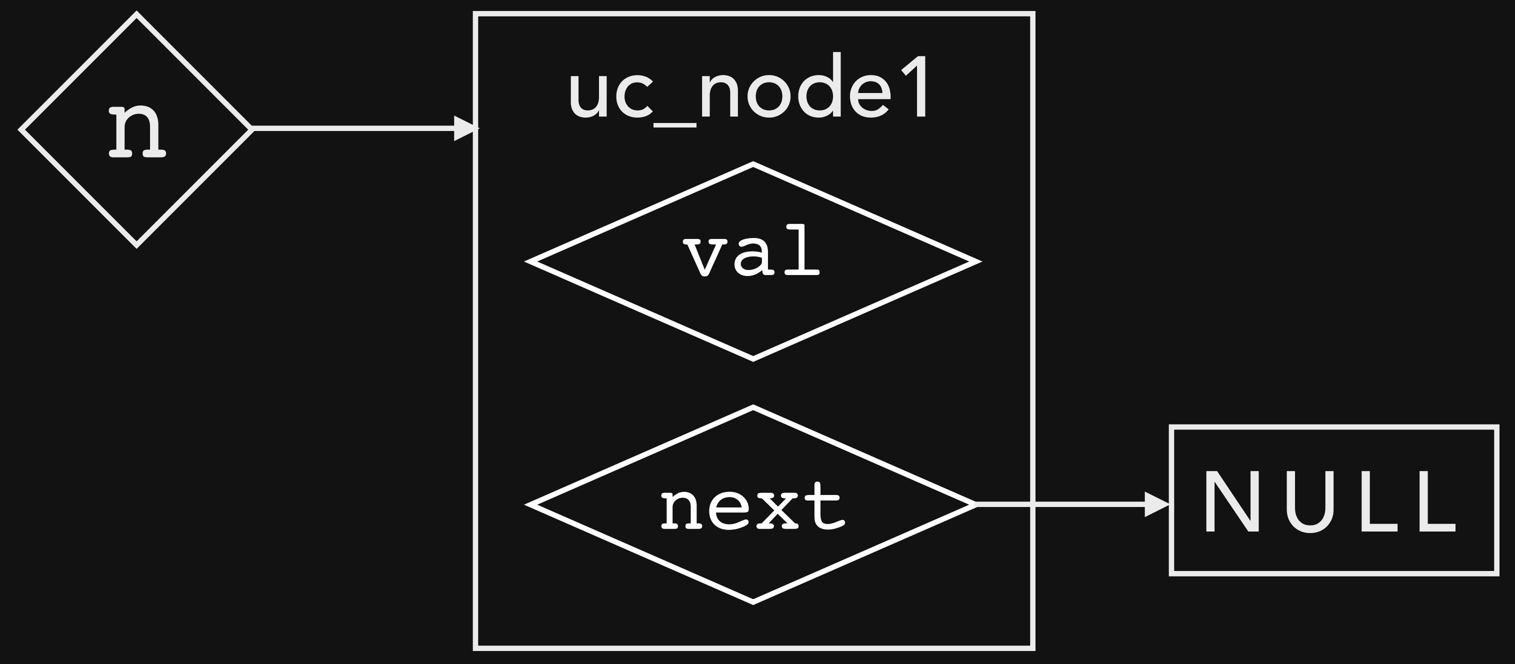

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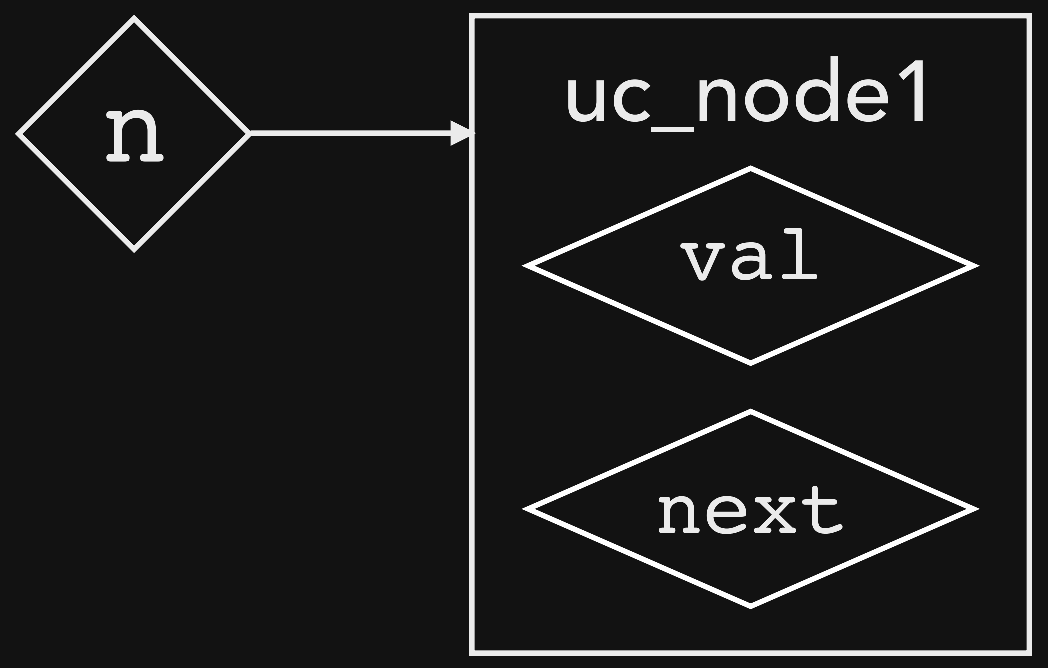

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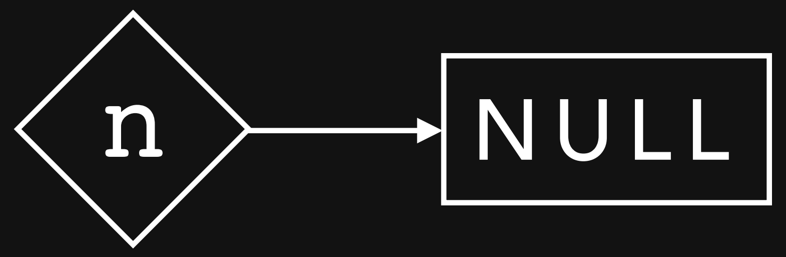

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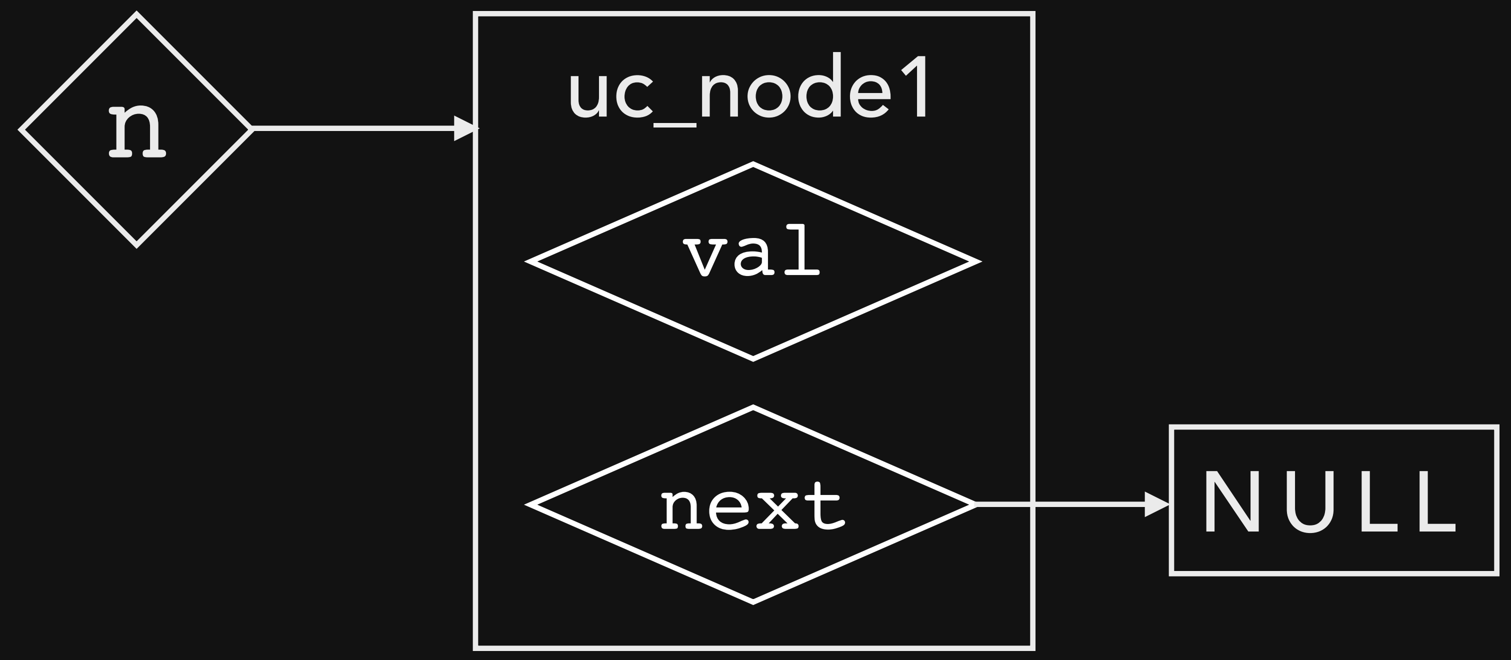
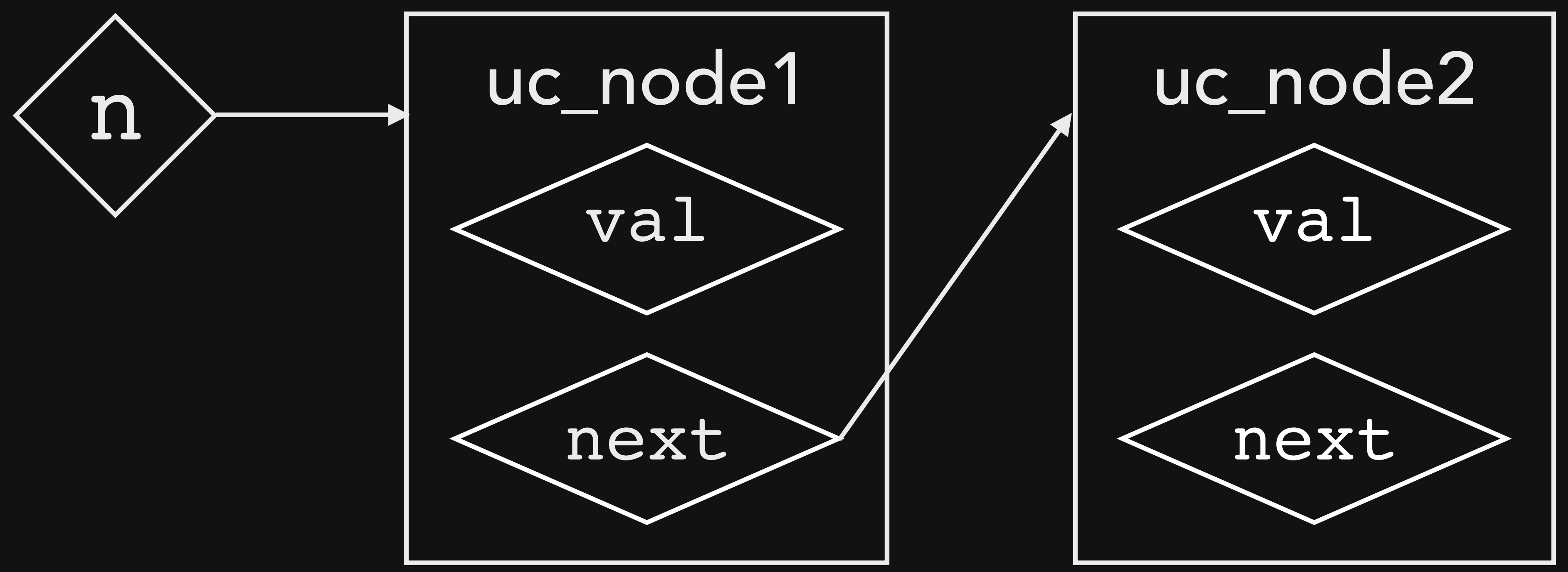


n != 0 | **n == &uc_node1** | **uc_node1.next == &uc_node2**



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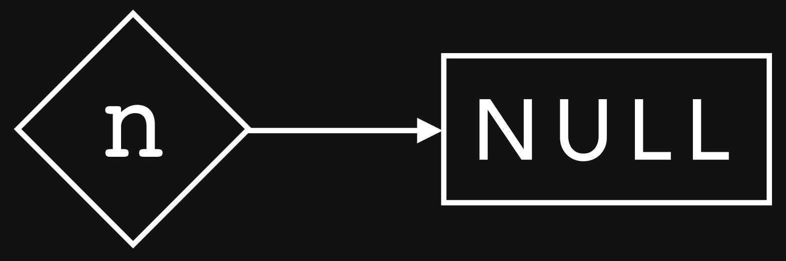

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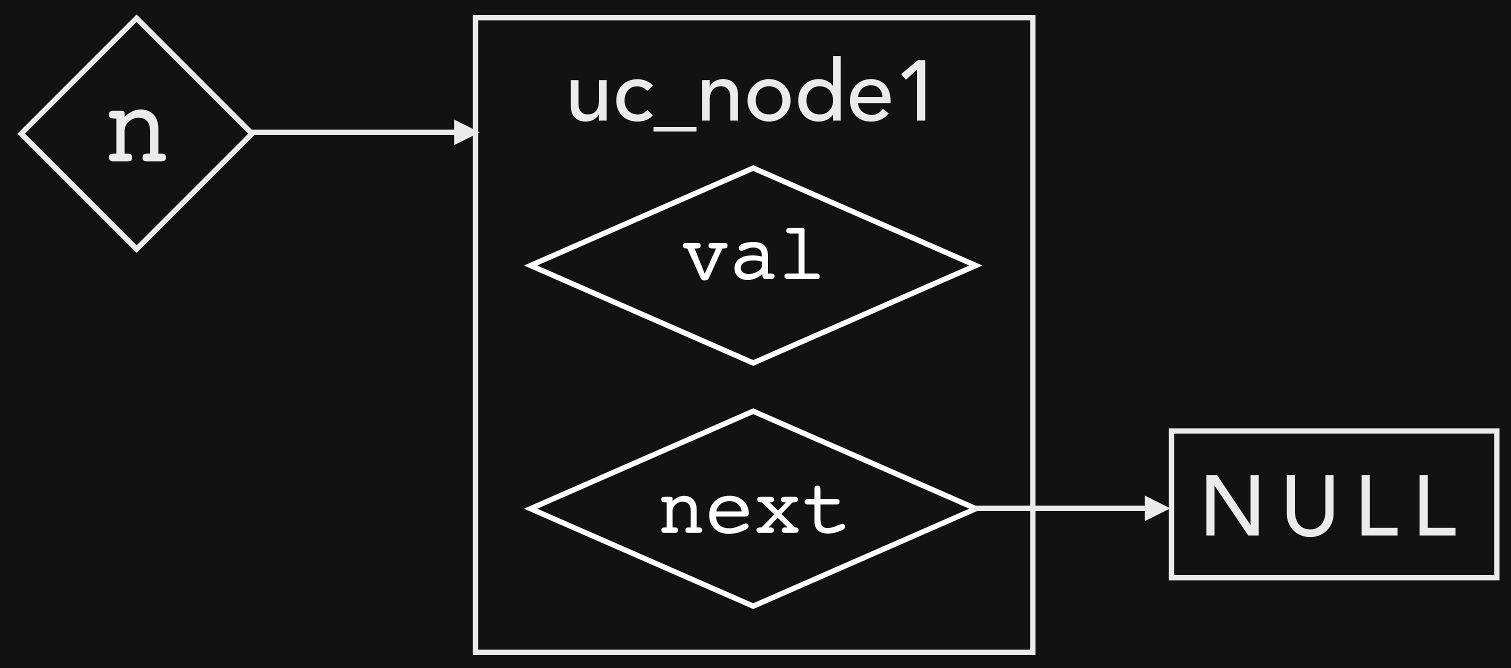

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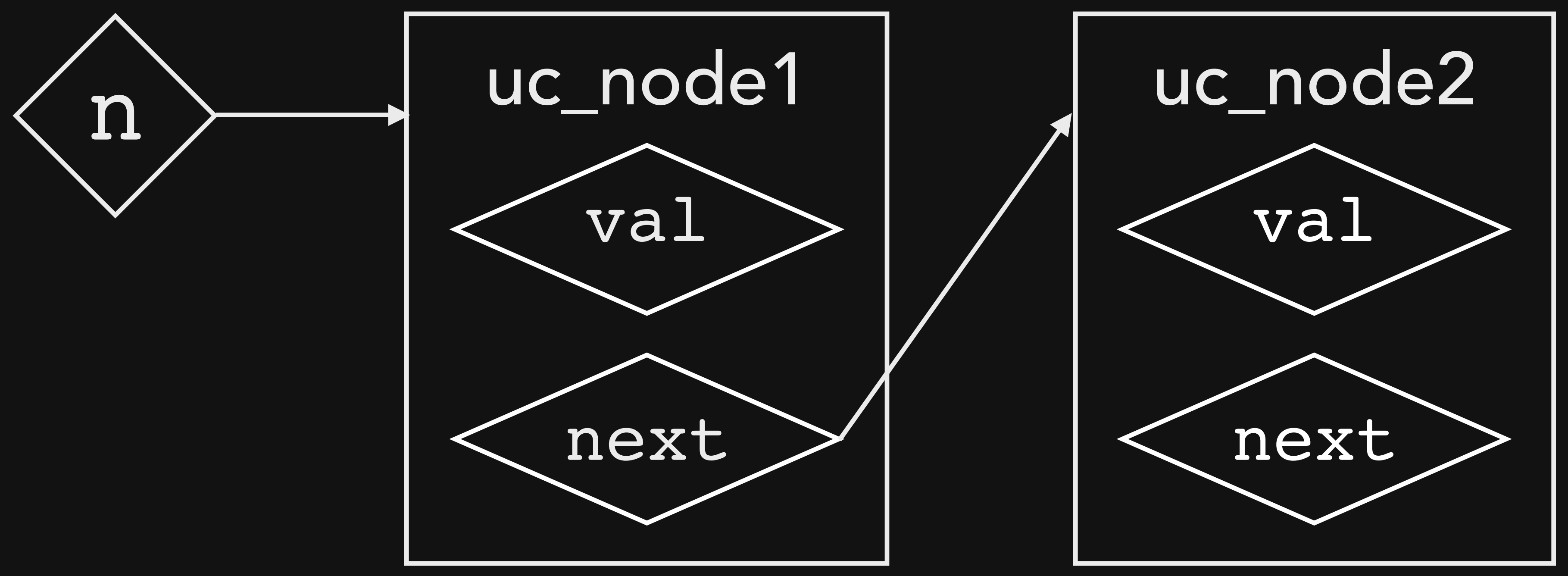

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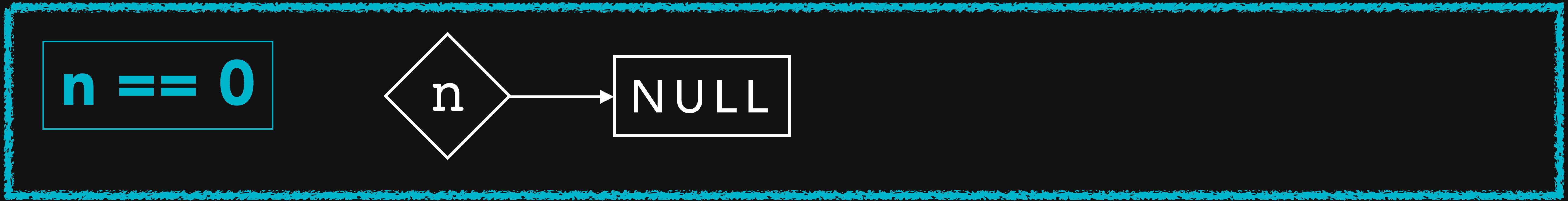

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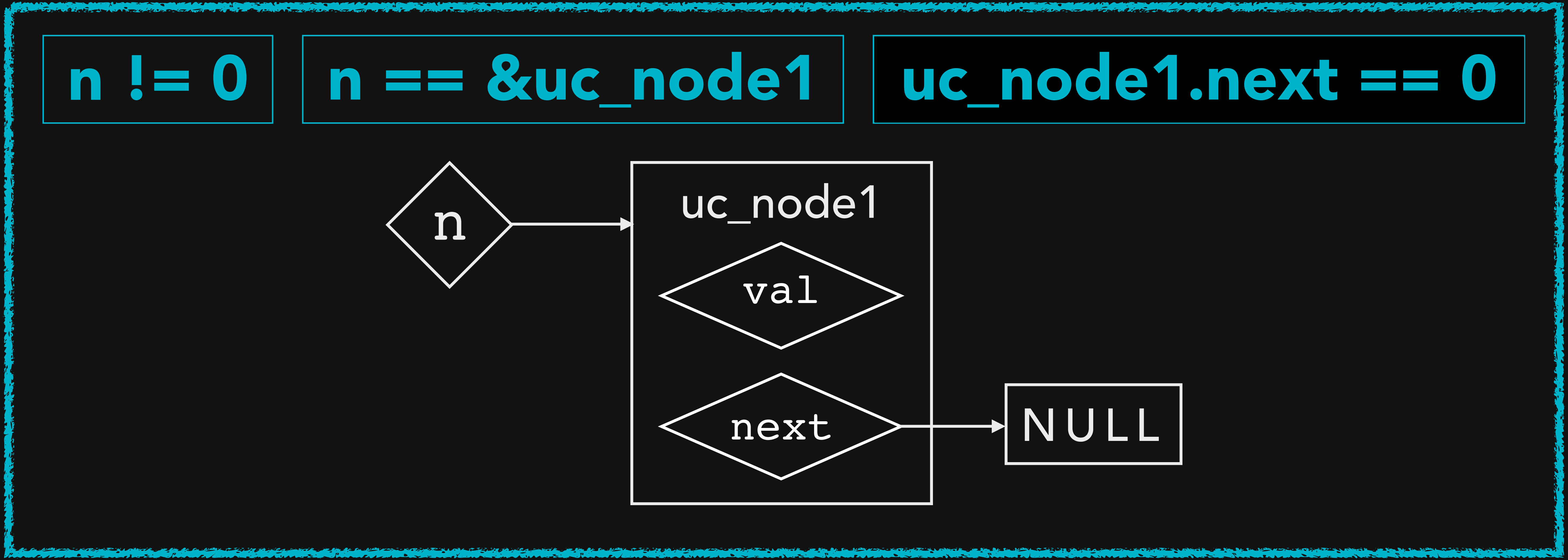

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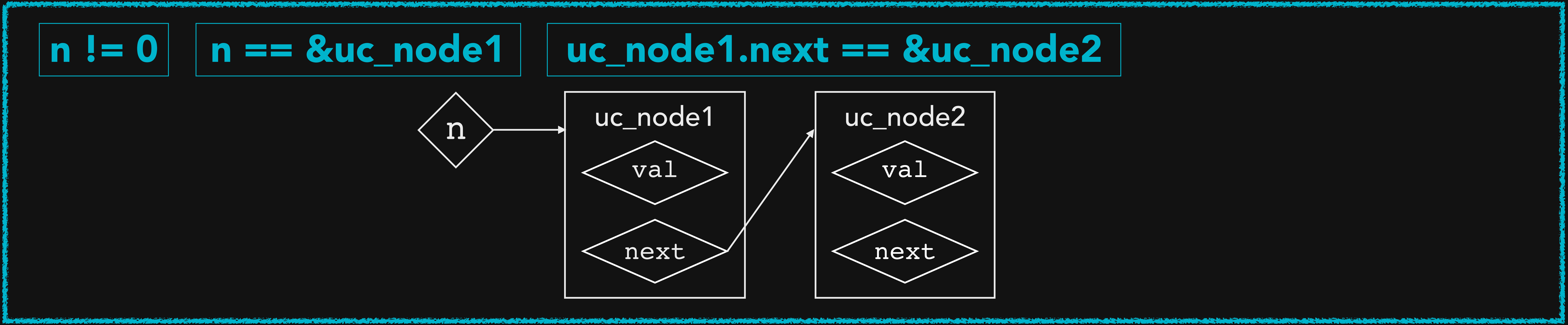

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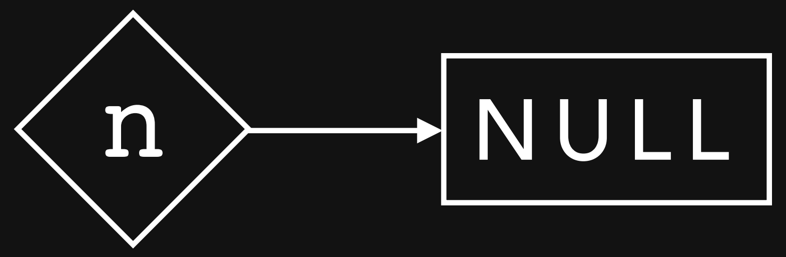

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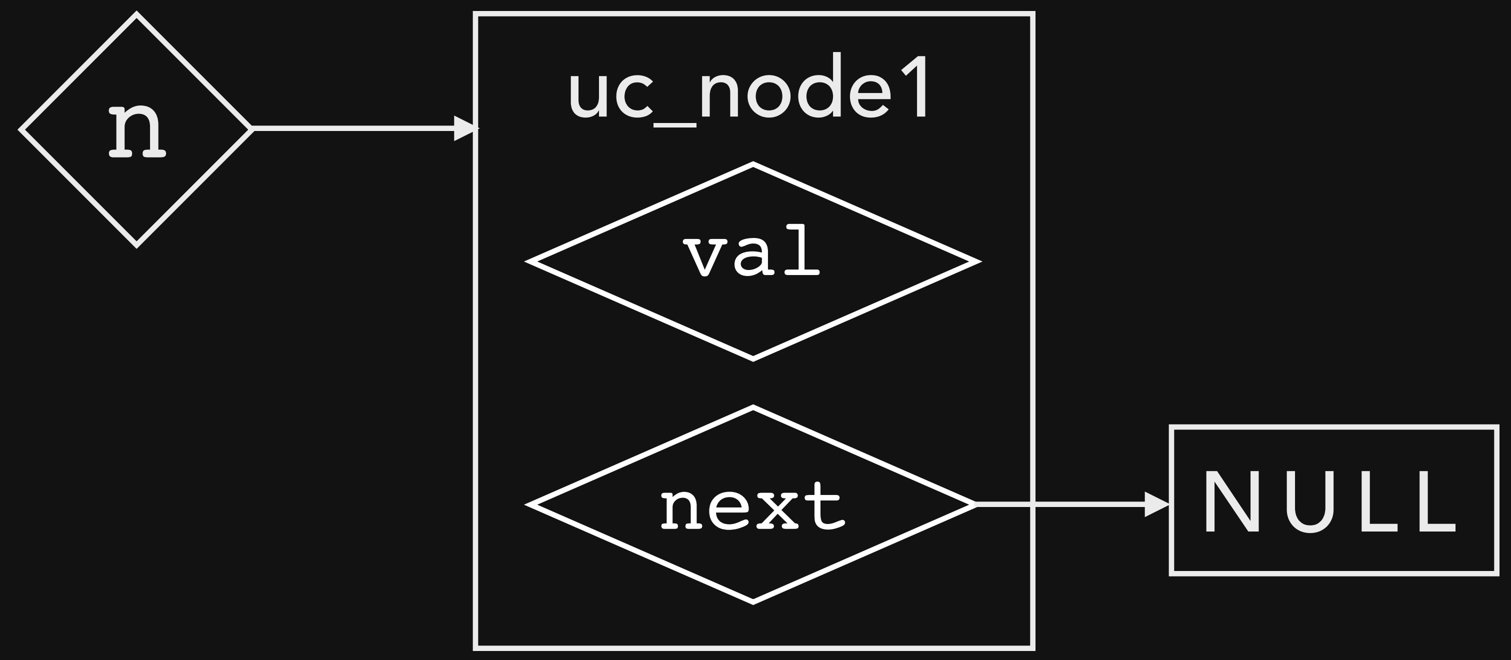

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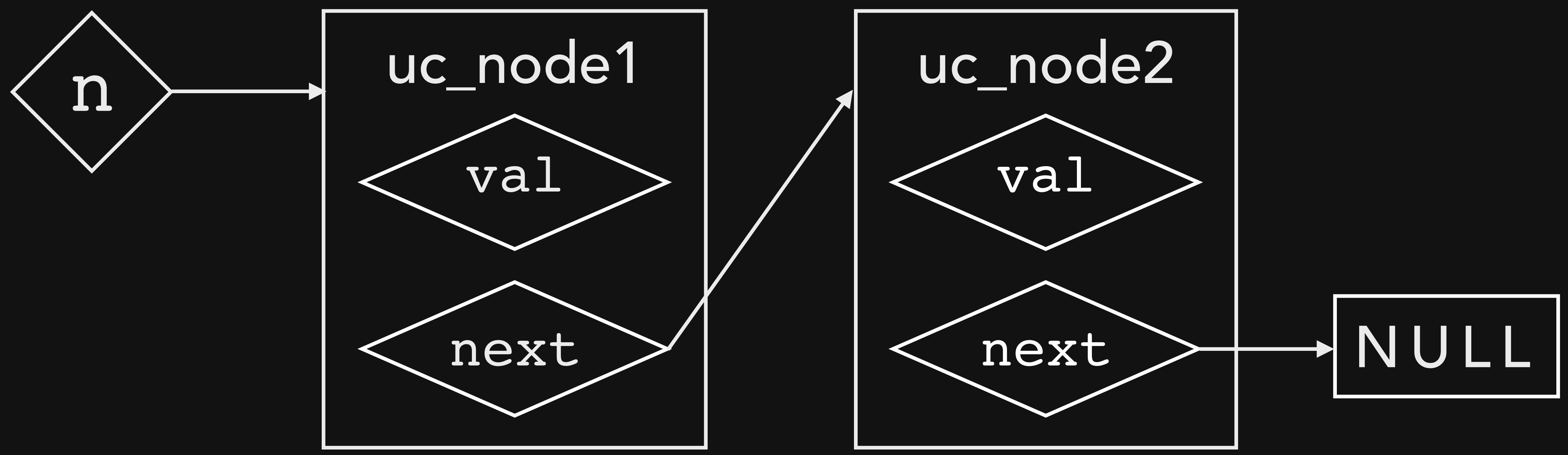
uc_node1.next == &uc_node2

uc_node2.next == 0



EXAMPLE

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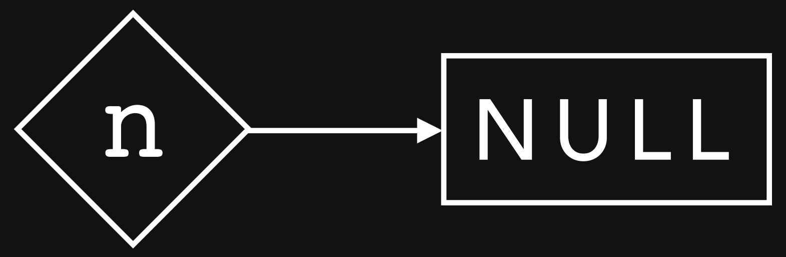

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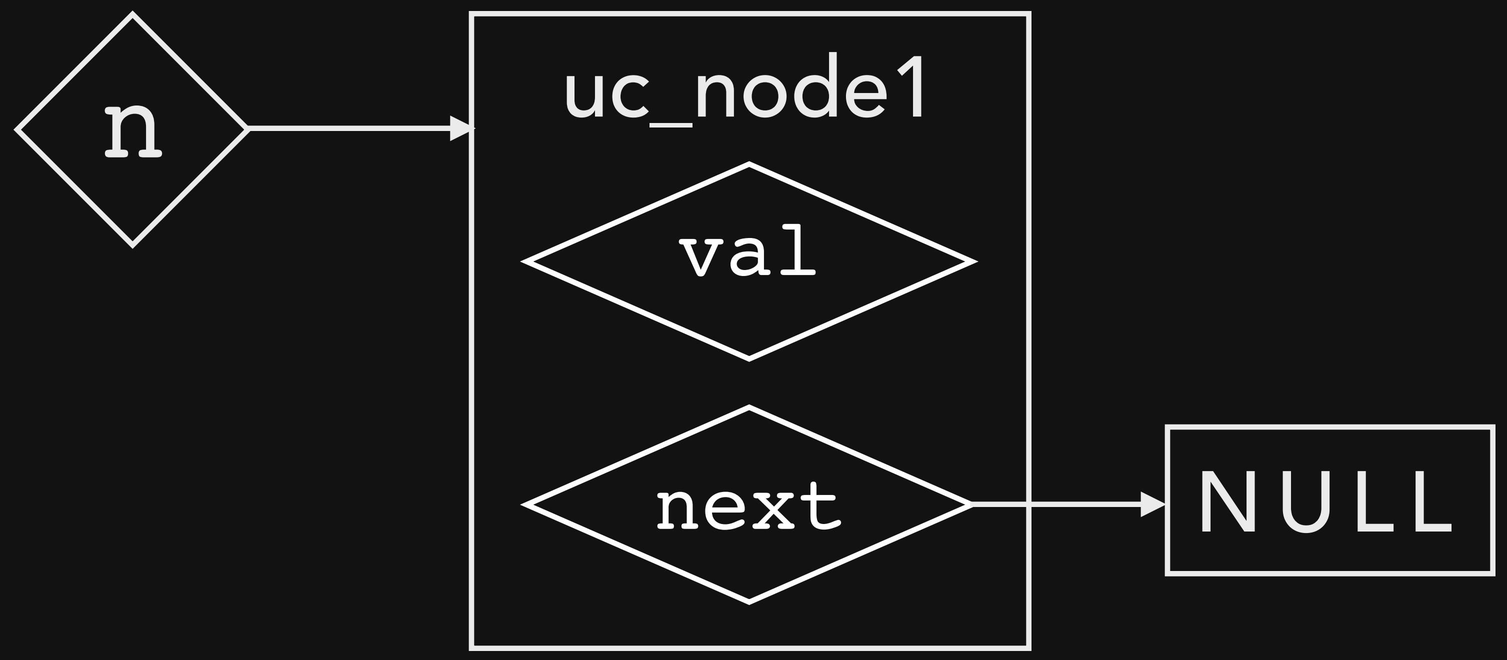

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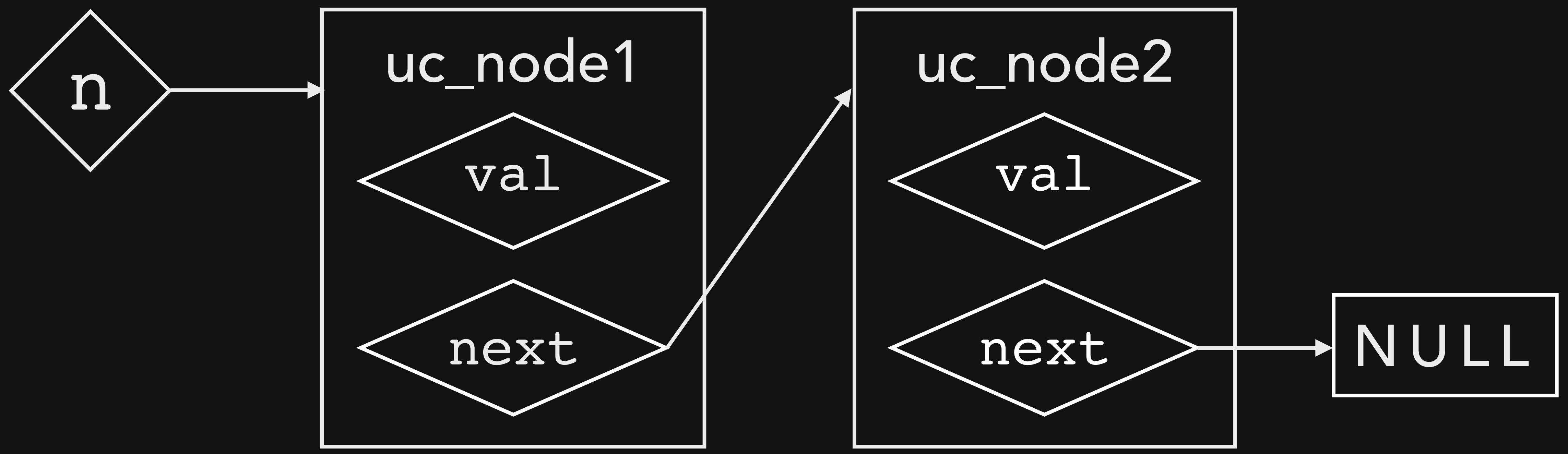


USE CASES

- Equivalence checking: **patches**
  - Yesterday’s code vs. today’s code (i.e., **fewer** bugs today)
  - Goal: detect (and prevent!) new **crashes** introduced by patches
  - Other uses discussed in CAV 2011 paper

PATCHES

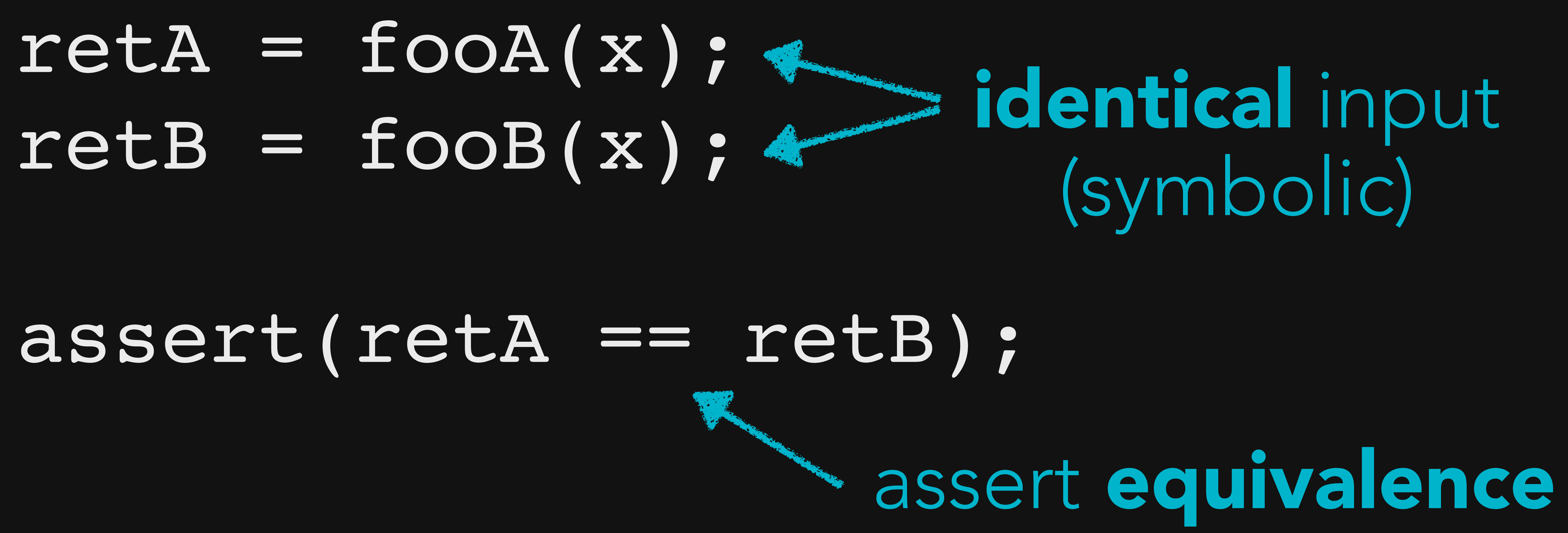
99 little bugs in the code.
99 little bugs in the code.
Take one down, patch it around.
127 little bugs in the code...

Source: https://twitter.com/phabricator

USE CASES

- Equivalence checking: **patches**
  - Yesterday's code vs. today's code (i.e., **fewer** bugs today)
  - Goal: detect (and prevent!) new **crashes** introduced by patches
  - Other uses discussed in CAV 2011 paper
- General bug-finding: **rule-based checkers**
  - Single version of a function; under-constrained + additional checker rules
  - Memory leaks, uninitialized data, unsafe user input
  - Simple interface for adding new checkers

EQUIVALENCE CHECKING



```
retA = fooA(x);
retB = fooB(x);

assert(retA == retB);
```

identical input
(symbolic)

assert **equivalence**

EQUIVALENCE CHECKING

- ~~Value equivalence~~
  - ~~Return value~~
  - ~~Arguments passed by reference~~
  - ~~Global/static variables~~
  - ~~System call effects (modeled)~~
- Error (crash) equivalence
  - Both versions typically have the same same (unknown) preconditions!
  - Neither version crashes on an input
  - Both versions crash on an input

USE CASE: whether patches introduce **crashes**

EQUIVALENCE CHECKING

- Check **per path** equivalence of two functions
- If **all paths** exhausted, equivalence <u>verified</u> (up to input bound)

EVALUATION

- BIND, OpenSSL
  - Mature, security-critical codebases (~400 KLOC each)
- Patches
  - BIND: 487 patches to 9.9 stable (14 months)
  - OpenSSL: 324 patches to 1.0.1 stable (27 months)
- Ran UC-KLEE for 1 hour on each patched function

EVALUATION: PATCHES

- Discovered **10 new bugs** (4 in BIND, 6 in OpenSSL)
  - 2 OpenSSL DoS vulnerabilities:
    - CVE-2014-0198: NULL pointer dereference
    - CVE-2015-0292: Out-of-bounds `memcpy` read
- Verified (w/ caveats) that patches do not introduce crashes
  - 67 (13.8%) for BIND, 48 (14.8%) for OpenSSL
  - Caveat: max. input size (25KB), tool limitations/bugs

OPENSSL CVE-2014-0198

```
do_ssl3_write():
if (wb->buf == NULL)
  if (!ssl3_setup_write_buffer(s))
    return -1;
...
/* If we have an alert to send, lets send it */
if (s->s3->alert_dispatch) {
  i=s->method->ssl_dispatch_alert(s);
  if (i <= 0)
    return(i);
  /* if it went, fall through and send more stuff */
}
...
unsigned char *p = wb->buf;
*(p++)=type&0xff;
```

NULL pointer check

call sets wb->buf to NULL

NULL pointer dereference

OPENSSL CVE-2014-0198

- Uncommon code path
  - SSL_MODE_RELEASE_BUFFERS runtime option (used by Apache mod_ssl)
  - SSL alert pending (could be triggered by attacker)
  - Difficult to consider this case with traditional testing

FALSE POSITIVES

- Function's inputs have unknown **preconditions**
- Partial solutions
  - Automated heuristics
  - Manual annotations (lazily, as needed)
    - Written in C/C++, separate from codebase
    - Simple annotation can silence **many** errors

FALSE POSITIVES: EXAMPLE (BIND)

```c
int isc_region_compare(isc_region_t *r1, isc_region_t *r2) {
  unsigned int l;
  int result;

  REQUIRE(r1 != NULL);
  REQUIRE(r2 != NULL);

  l = (r1->length < r2->length) ? r1->length : r2->length;

  if ((result = memcmp(r1->base, r2->base, l)) != 0)
    return ((result < 0) ? -1 : 1);
  else
    return ((r1->length == r2->length) ? 0 :
            (r1->length < r2->length) ? -1 : 1);
}
```

```c
INVARIANT(r->length <= OBJECT_SIZE(r->base));
```

623 errors silenced (7.5% of all errors reported for BIND)

MANUAL ANNOTATIONS

- BIND: 400 lines of annotation code (~0.1%)
- OpenSSL: 60 lines of annotation code (~0.02%)
- Reasonable effort relative to code size (~400 KLOC) and importance

GENERAL BUG-FINDING

- Run **single version** of a function (w/ lazy initialization)
- Individual checkers look for specific types of bugs:
  - Leak checker
  - Uninitialized data checker
  - User input checker
- Like Valgrind but applied to **all execution paths**

EVALUATION

- 20,000+ functions: BIND, OpenSSL, Linux kernel (~12 MLOC)
- Found 67 new bugs
  - 37 memory leaks
    - Linux kernel: exploitable AUTH_GSS leak in NFS SunRPC layer
  - 19 uses of uninitialized data
    - BIND: DNS UDP port PRNG selected by uninitialized value
    - Linux kernel: leak of private kernel stack data via firewire ioctl
  - 11 unsafe user input (Linux kernel only)
    - VMware VMCI driver: unchecked memcpy length (~Heartbleed)
    - CEPH distributed file system: division-by-zero (kernel FPE)

USER INPUT CHECKER

- User input is fully-constrained (an attacker may supply any value); no unknown input preconditions
- Checker tracks whether each symbolic byte is UC/FC
- Checker emits UNSAFE_INPUT flag if error is caused by FC input
- Suppresses flag for inputs possibly sanitized (false pos. trade-off)
- C annotations: specify functions returning user input
  - Linux: `get_user`, `copy_from_user`, syscall args
  - BIND: `isc_buffer_getuint8`
  - OpenSSL: byte-swaps (`n2s`, `n2l`, etc.) [Chou]

KERNEL VMCI VULNERABILITY

Fully constrained

copy_from_user()

```
static int dg_dispatch_as_host(...,
                               struct vmci_datagram *dg) {
  dg_size = VMCI_DG_SIZE(dg);
  ...
  dg_info = kmalloc(sizeof(*dg_info) +
        (size_t) dg->payload_size, GFP_ATOMIC);
  ...
  memcpy(&dg_info->msg, dg, dg_size);
  ...
}
```

Unchecked **memcpy** length

Send up to 69,632 bytes from host private kernel memory to guest OS

Similar to Heartbleed! (much lower impact)

CONCLUSION

- Under-constrained symbolic execution
- Equivalence checking: patches
- General bug-finding: rule-based checkers
- Experimental results: BIND, OpenSSL, Linux kernel

QUESTIONS?

@ramosbugs