Source-based code coverage of Linux kernel

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  - Aviation: DO-178C
  - Rail: EN 50128
  - Automotive: ISO 26262

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- For testing: improve software quality
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Related (past) talk:
“Measuring and Understanding Linux Kernel Tests”
Kernel Testing & Dependability MC

- For certification
  - Aviation: DO-178C
  - Rail: EN 50128
  - Automotive: ISO 26262

Related (past) talk:
“Making Linux Fly: Towards a Certified Linux Kernel”
Refereed track

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Both can only be **approximately** correlated to source code.
Both are **susceptible to optimization**.

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static struct drm_buddy_block *
__get_buddy(struct drm_buddy_block *block)
{
    struct drm_buddy_block *parent;

    parent = block->parent;
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        return NULL;


    if (parent->left == block)
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                  if (parent->left == block)
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N_1                 if (!parent)
N_2                     return NULL;  /* then clause */

                    /* else clause */
N_1-N_2             if (parent->left == block)
N_3                     return parent->right;


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            $N_1$      if (!parent)
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                         “True”  outcome taken   ??    times
                         “False” outcome taken   ??    times
      $N_1$-$N_2$      if (parent->left == block)
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        N1        parent = block->parent;
        N1        if (!parent)
        N2            return NULL;
                     “True”  outcome taken   N2     times
                     “False” outcome taken  N1-N2   times
     N1-N2        if (parent->left == block)
        N3            return parent->right;
                     “True”  outcome taken   N3     times
                     “False” outcome taken N1-N2-N3 times
  N1-N2-N3        return parent->left;
              }
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	`__get_buddy(struct drm_buddy_block *block)`
	`{`
N_1-N_2	`    if (parent->left == block)`
N_3	`        return parent->right;`
	“True” outcome taken N_3 times “False” outcome taken $N_1-N_2-N_3$ times
$N_1-N_2-N_3$	`    return parent->left;`
	`}`

`drivers/gpu/drm/drm_buddy.c`

This is exactly our goal:
precise source correlation regardless of optimization level.

`gcov` reports in reality

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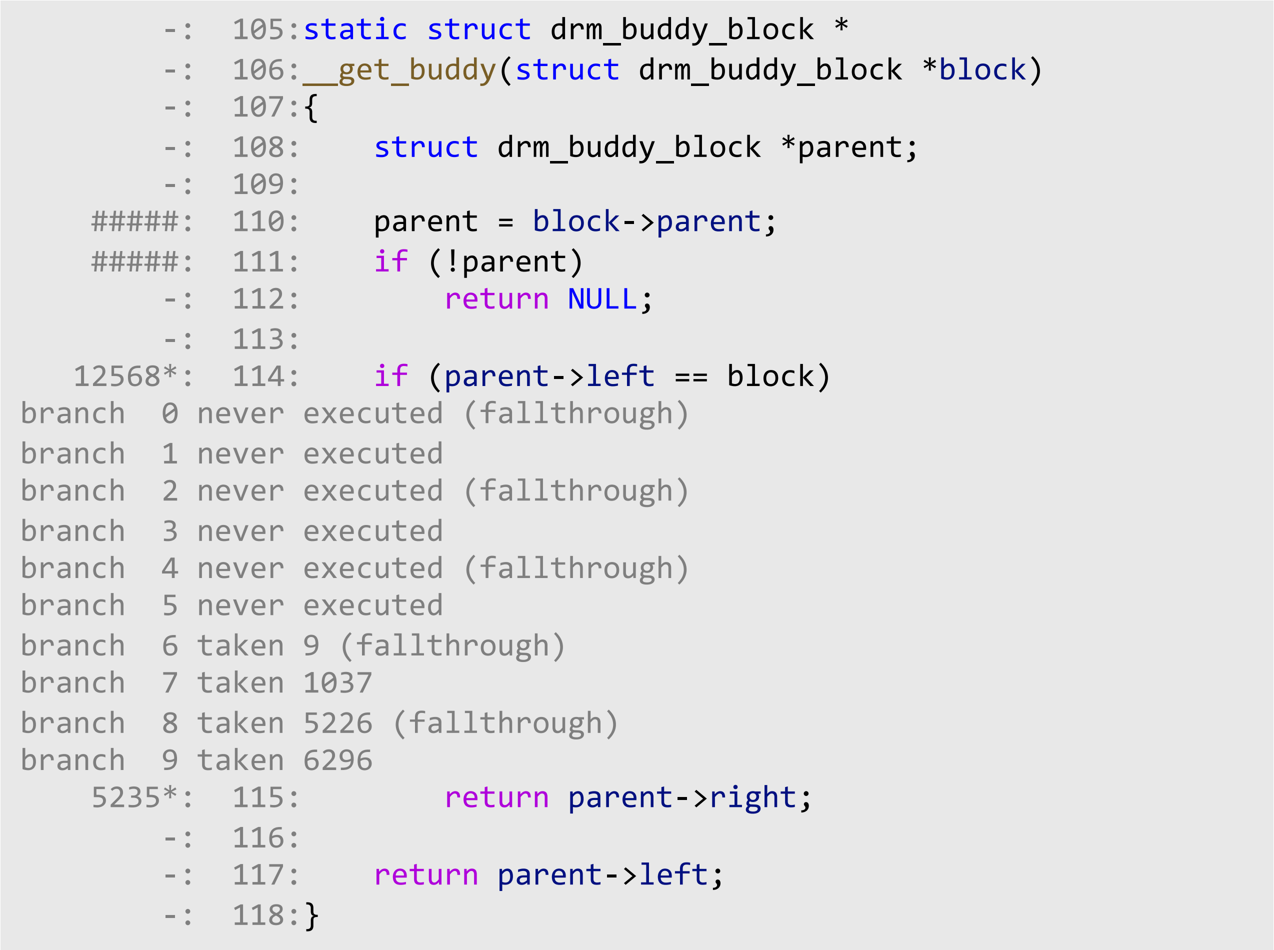

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        -:  105:static struct drm_buddy_block *
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`drivers/gpu/drm/drm_buddy.c`

- Setup
  - Kernel version: `v6.10-rc7`
  - Options
    - `defconfig`
    - `CONFIG_KUNIT_ALL_TESTS`
    - Default optimization level
  - Measurement span: kernel boot with all KUnit tests

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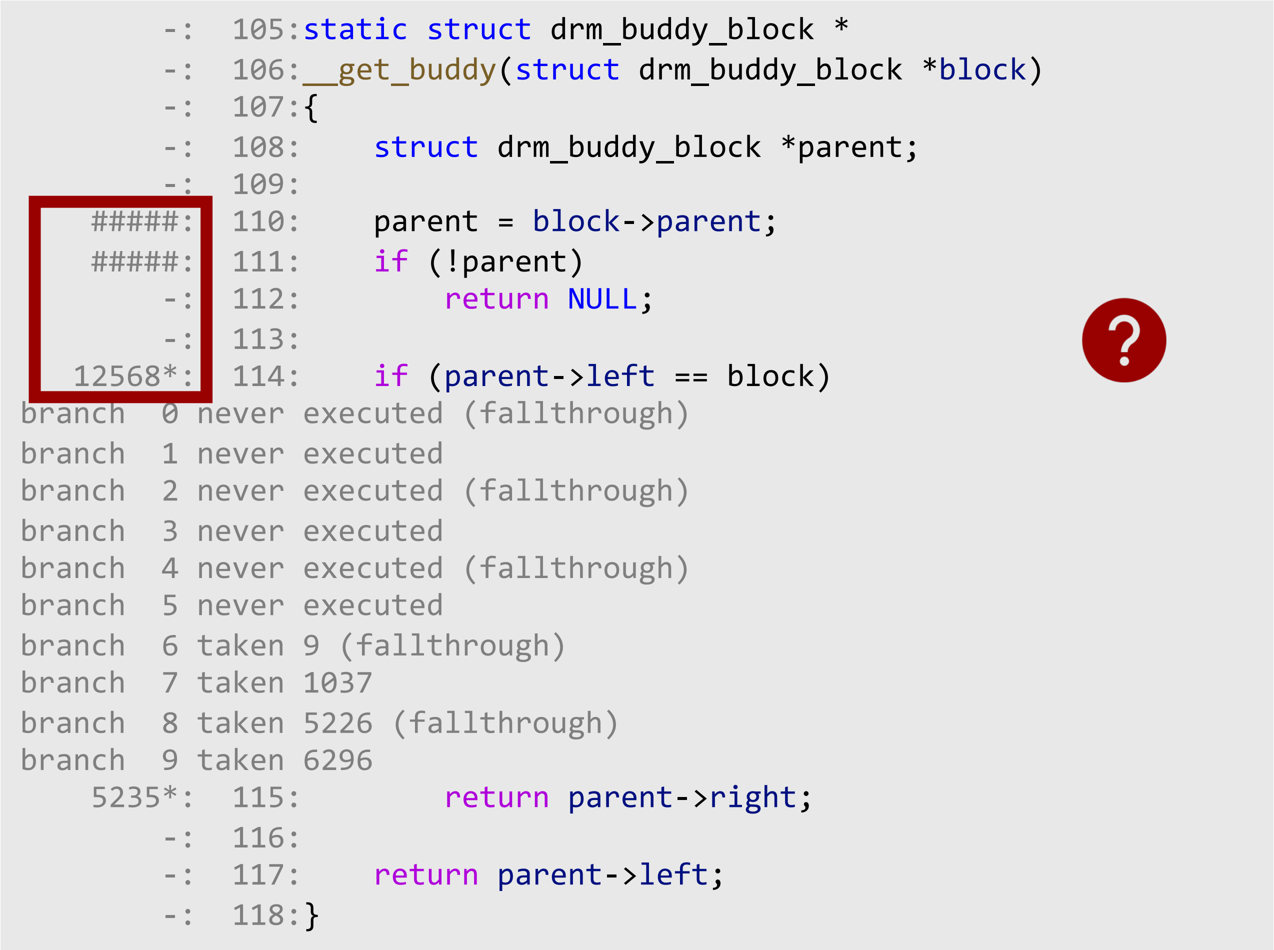

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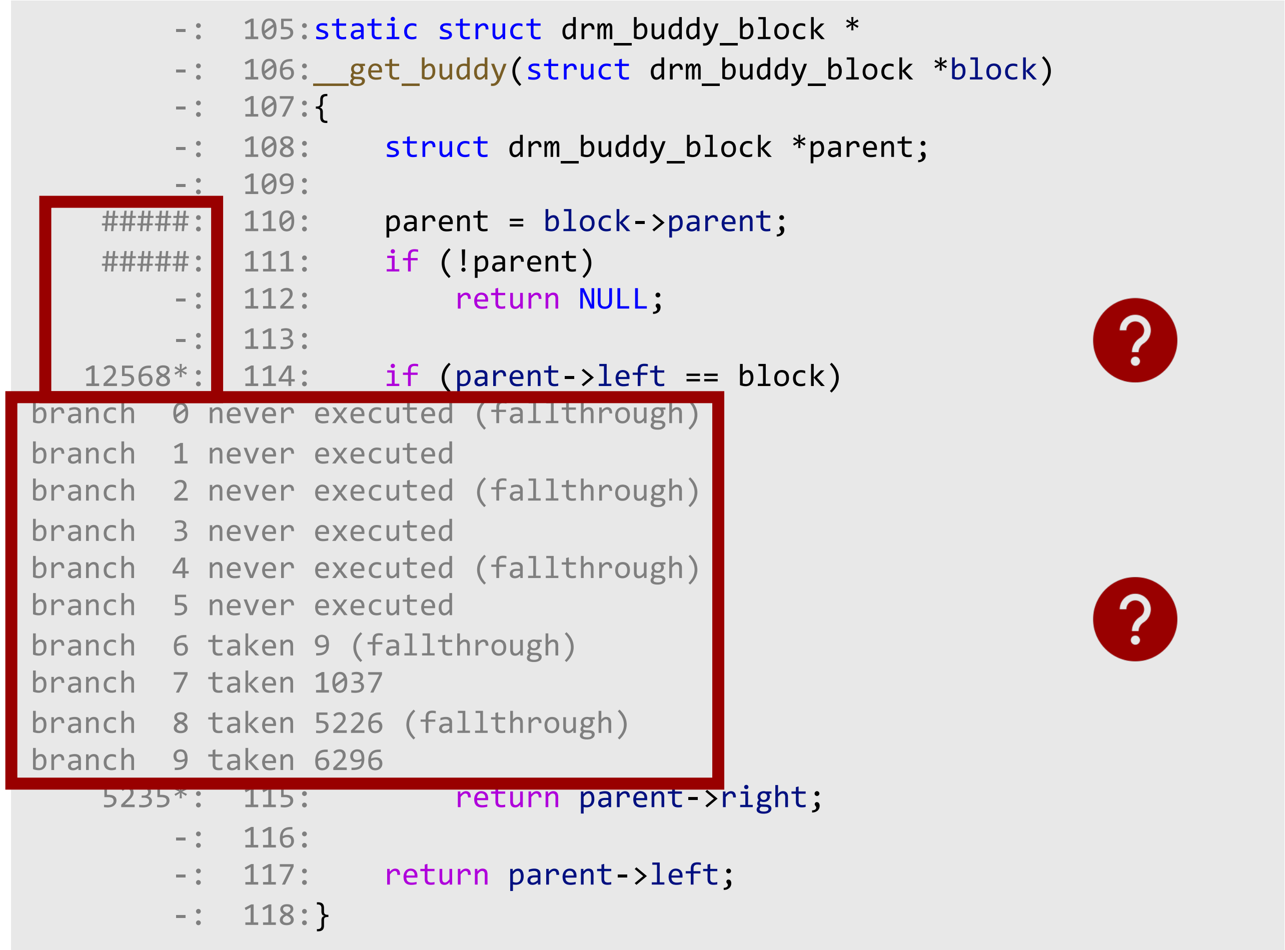

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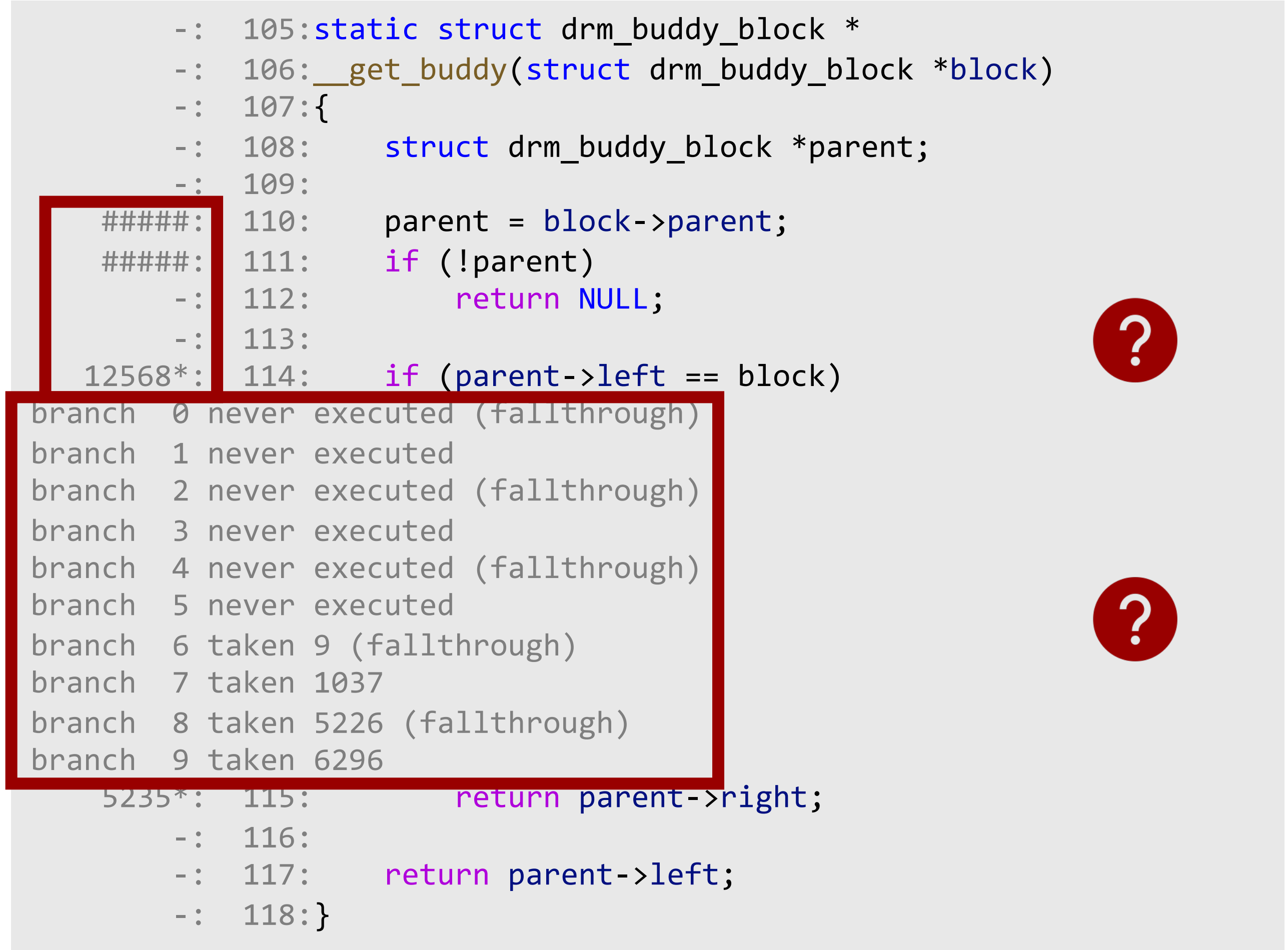

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- Branch coverage:
  - A simple `if` statement is reported to have 10 outcomes, instead of 2

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```
$ clang -fprofile-instr-generate -fcoverage-mapping foo.c -o foo
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$ llvm-profdata merge foo.profraw -o foo.profdata
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$ LLVM_PROFILE_FILE=foo.profraw ./foo
$ llvm-profdata merge foo.profraw -o foo.profdata
$ llvm-cov show ./foo -instr-profile=foo.profdata
```

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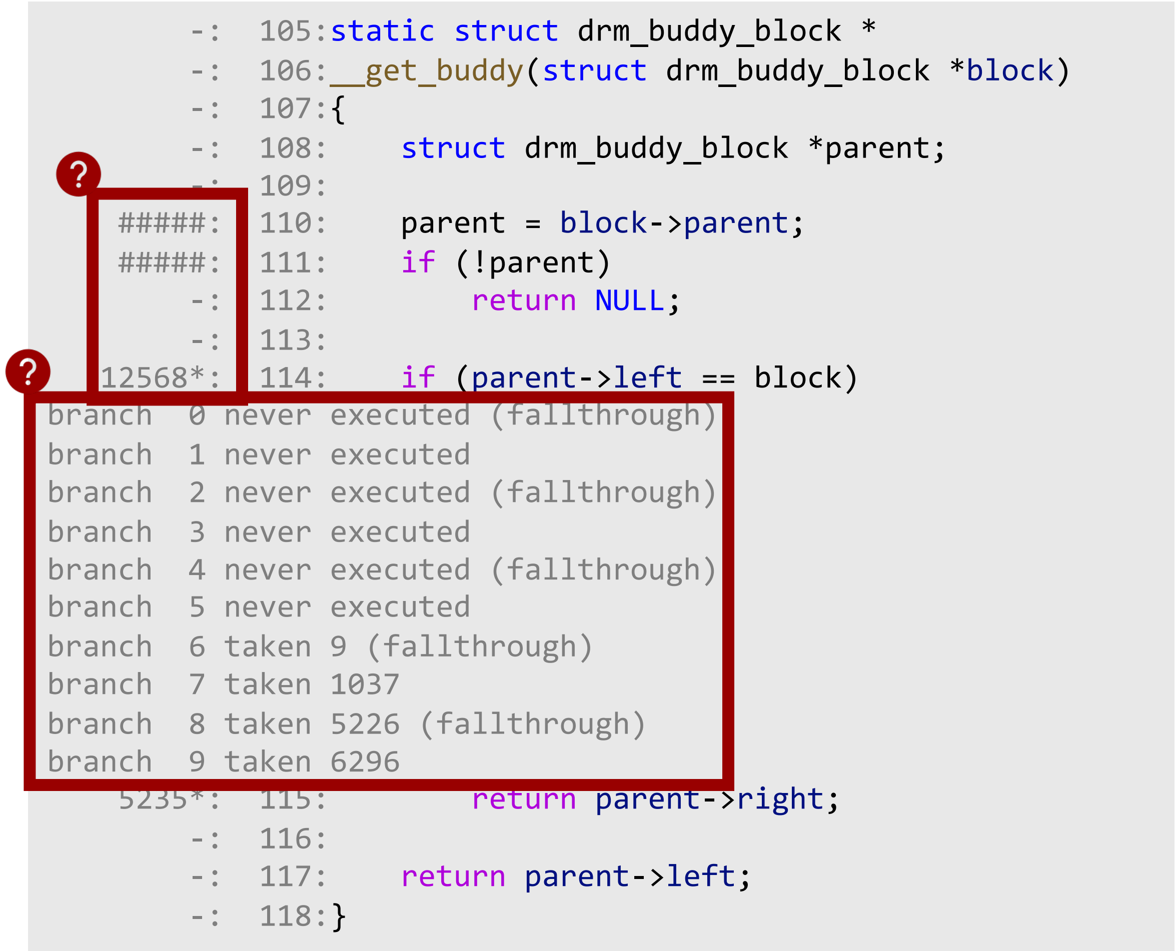
Compare gcov and llvm-cov reports



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    5235*:  115:        return parent->right;
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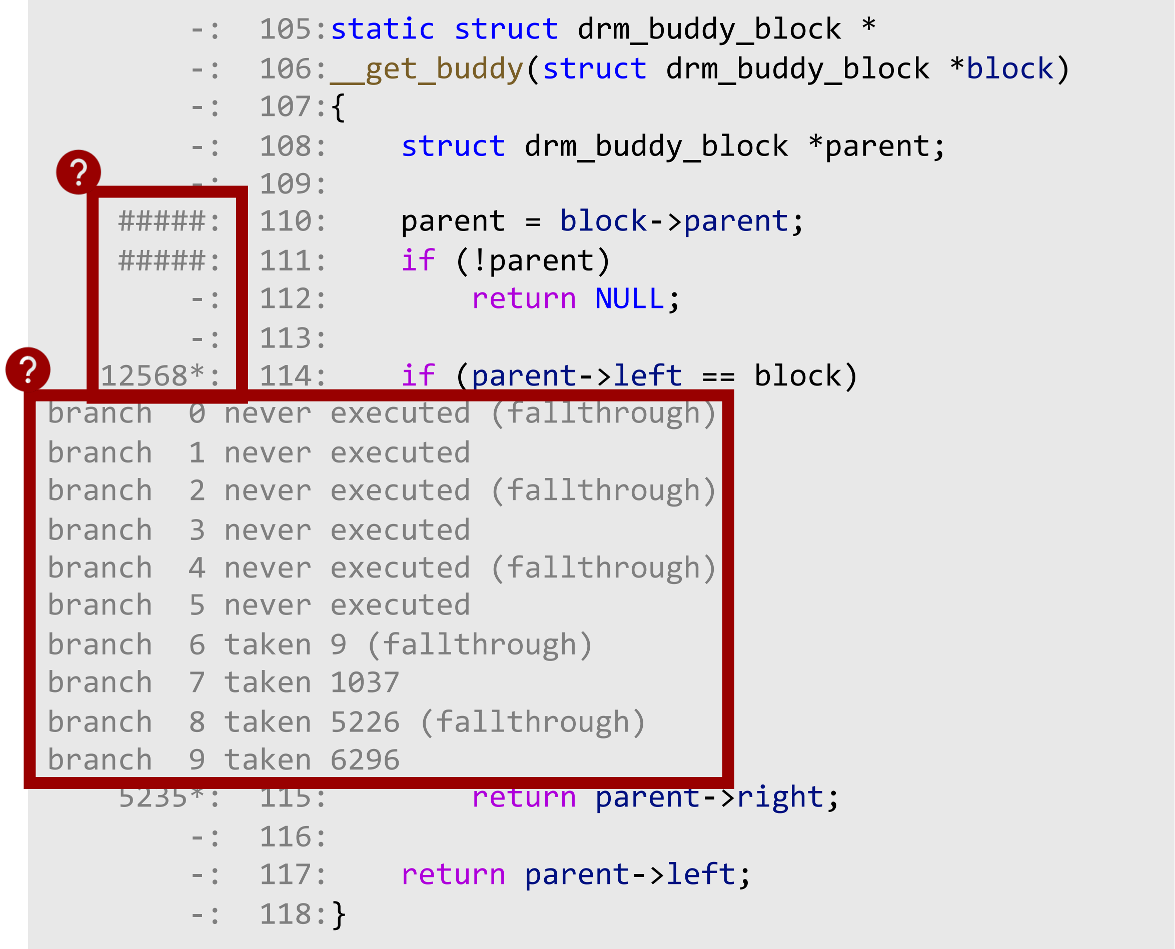
```

gcov (–O2)

drivers/gpu/drm/drm_buddy.c

Compare gcov and llvm-cov reports



```
        -:  105:static struct drm_buddy_block *
        -:  106:__get_buddy(struct drm_buddy_block *block)
        -:  107:{
        -:  108:    struct drm_buddy_block *parent;
        -:  109:
    #####:  110:    parent = block->parent;
    #####:  111:    if (!parent)
        -:  112:        return NULL;
        -:  113:
   12568*:  114:    if (parent->left == block)
branch  0 never executed (fallthrough)
branch  1 never executed
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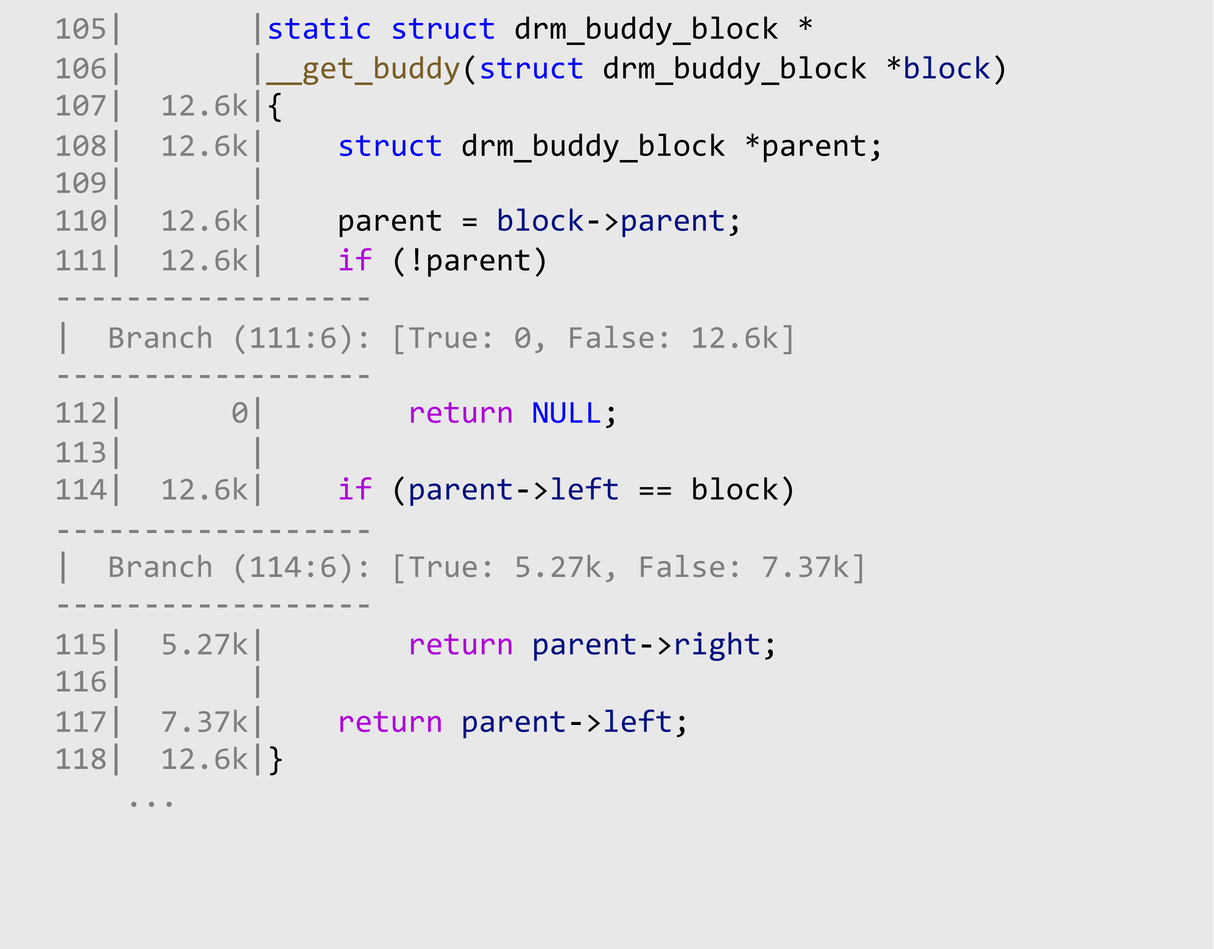

```
  105|       |static struct drm_buddy_block *
  106|       |__get_buddy(struct drm_buddy_block *block)
  107|  12.6k|{
  108|  12.6k|    struct drm_buddy_block *parent;
  109|       |
  110|  12.6k|    parent = block->parent;
  111|  12.6k|    if (!parent)
  ------------------
  |  Branch (111:6): [True: 0, False: 12.6k]
  ------------------
  112|      0|        return NULL;
  113|       |
  114|  12.6k|    if (parent->left == block)
  ------------------
  |  Branch (114:6): [True: 5.27k, False: 7.37k]
  ------------------
  115|  5.27k|        return parent->right;
  116|       |
  117|  7.37k|    return parent->left;
  118|  12.6k|}
     ...
```

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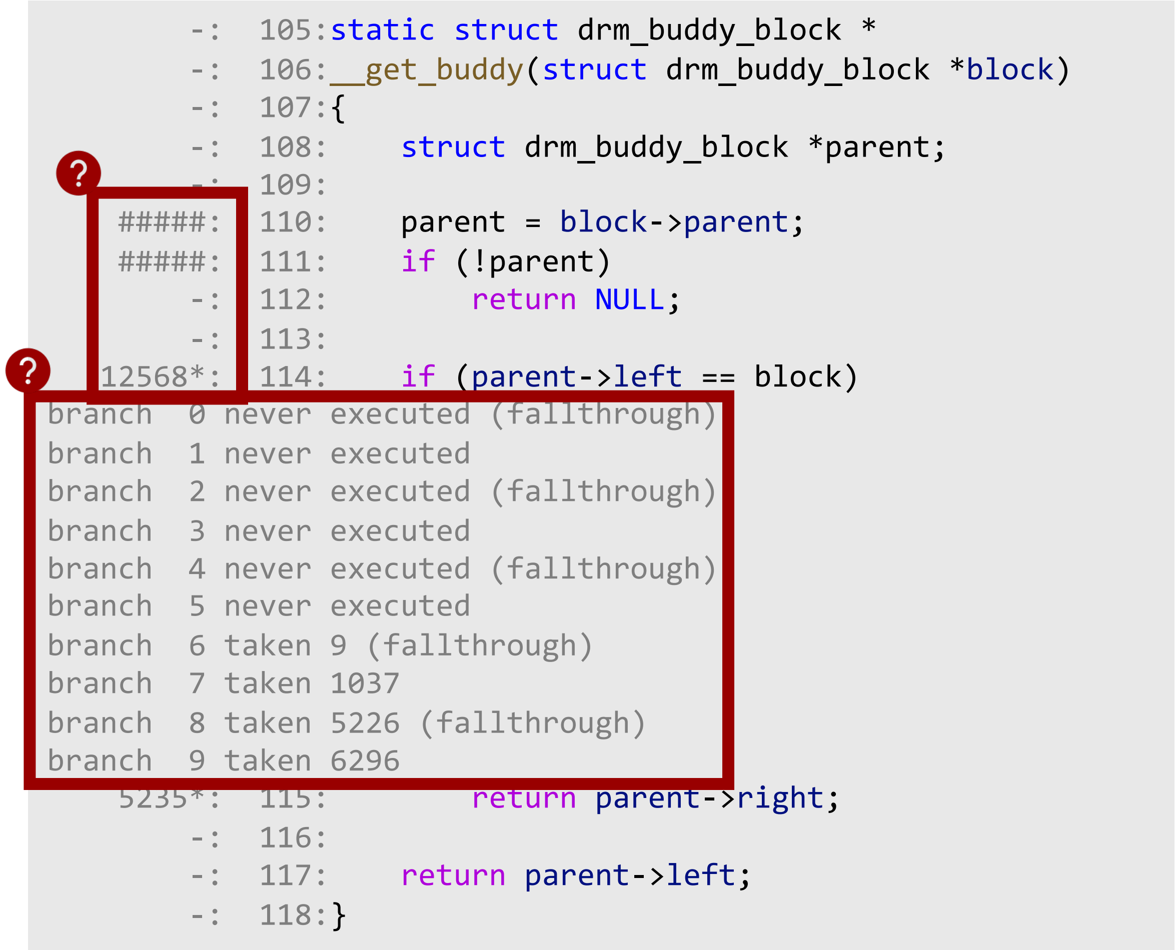

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        -:  105:static struct drm_buddy_block *
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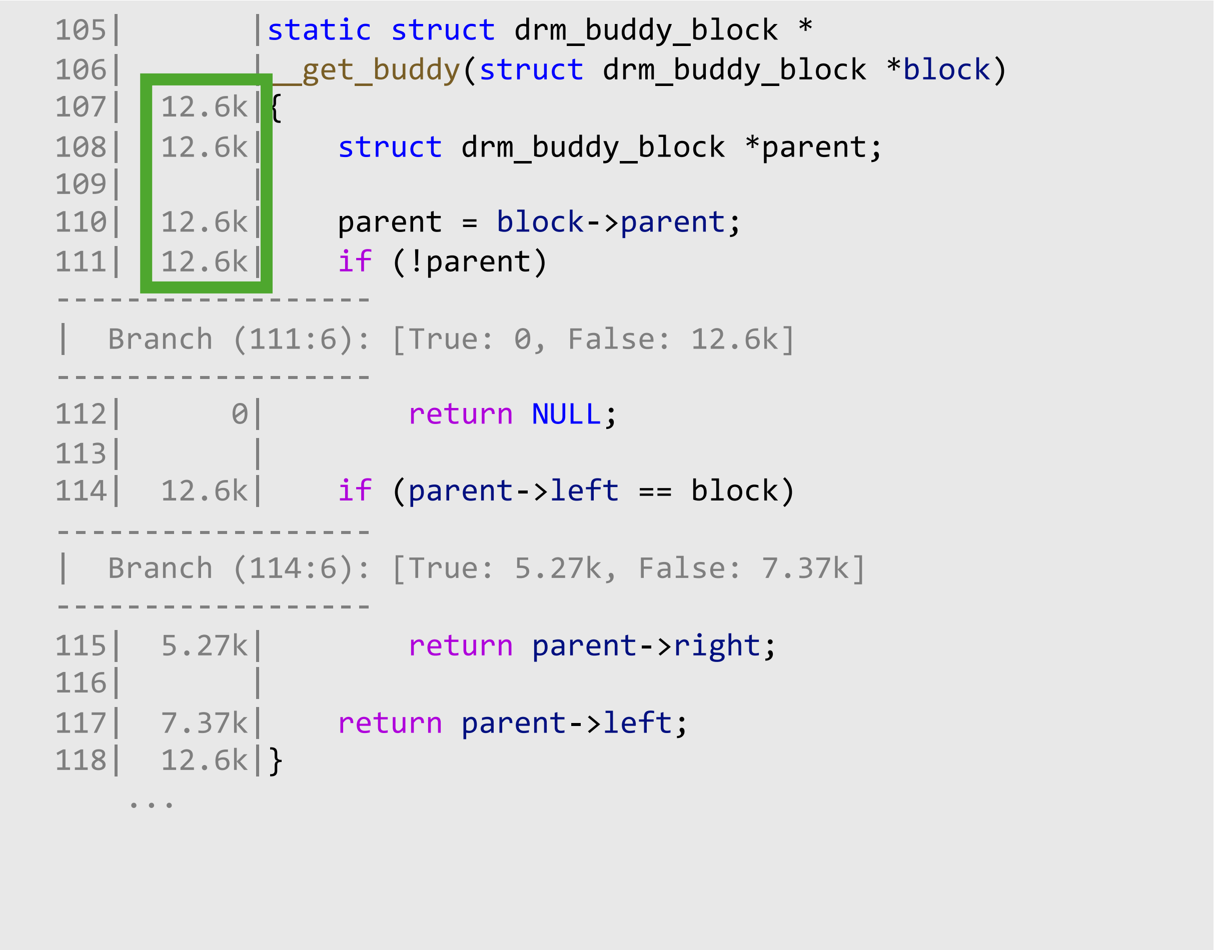

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  109|       |
  110|  12.6k|    parent = block->parent;
  111|  12.6k|    if (!parent)
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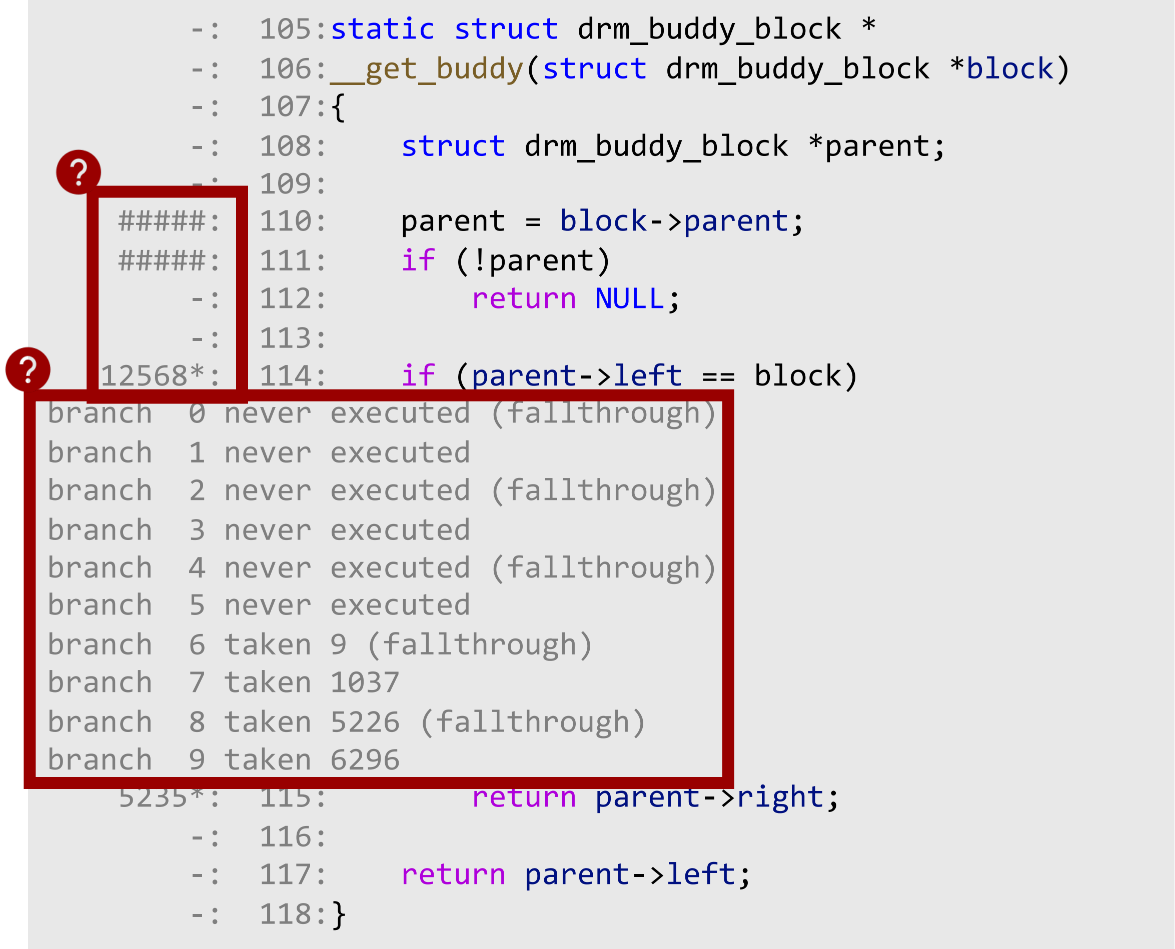

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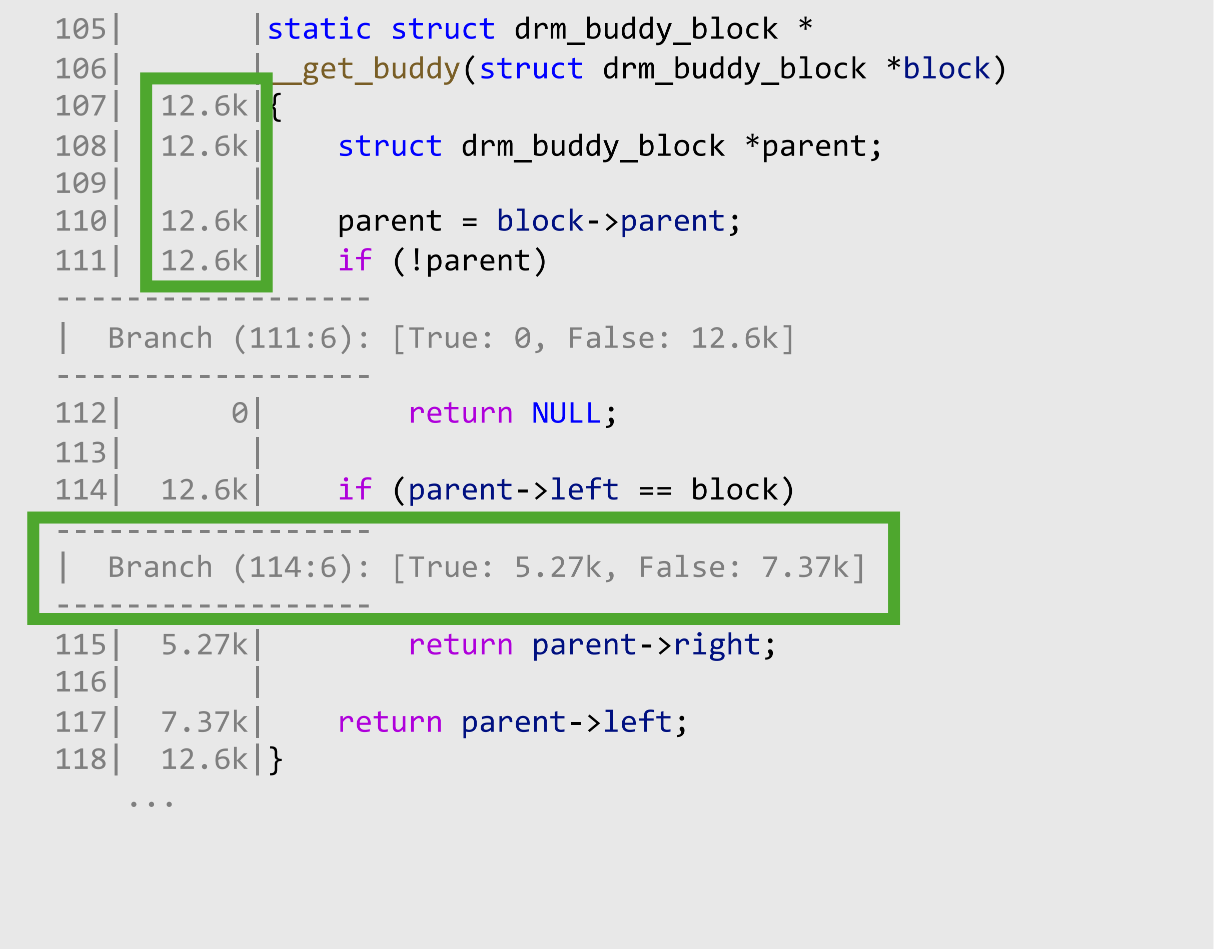
gcov (–O2)



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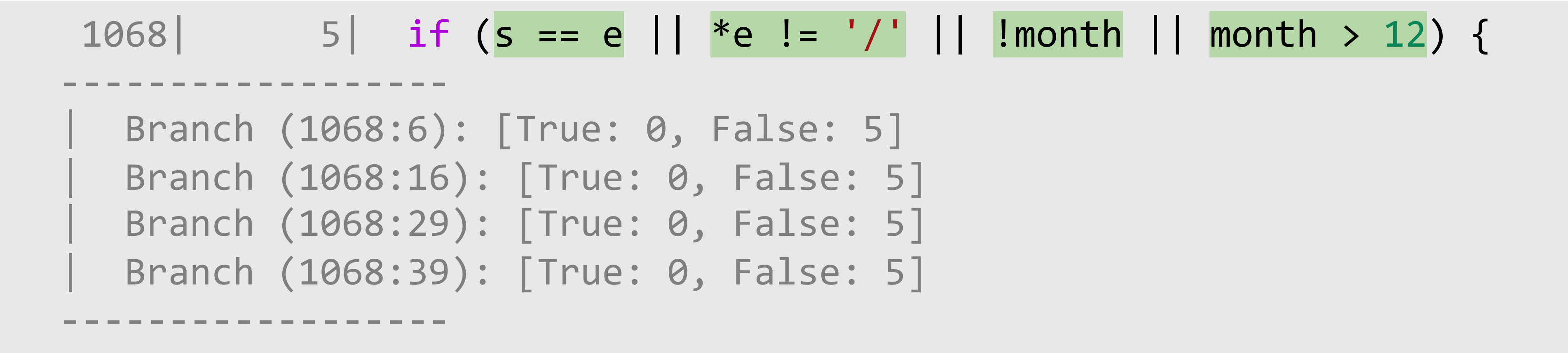
llvm-cov (–O2)

drivers/gpu/drm/drm_buddy.c

More examples: missing branch outcomes

gcov
(-O2)

llvm-cov
(-O2)



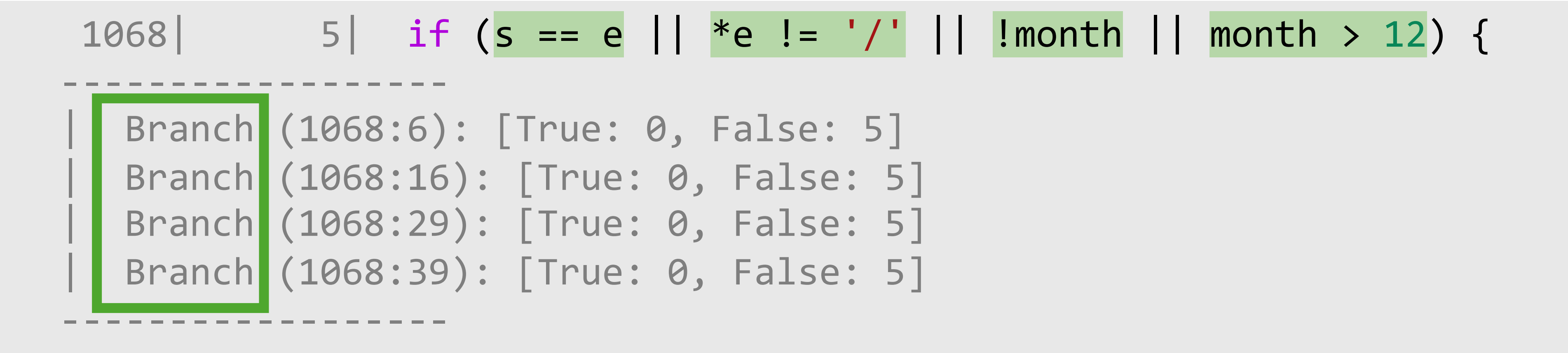
```
 1068|       5|  if (s == e || *e != '/' || !month || month > 12) {
------------------
|  Branch (1068:6): [True: 0, False: 5]
|  Branch (1068:16): [True: 0, False: 5]
|  Branch (1068:29): [True: 0, False: 5]
|  Branch (1068:39): [True: 0, False: 5]
------------------
```

`drivers/firmware/dmi_scan.c:dmi_get_date`

More examples: missing branch outcomes

gcov
(–O2)

llvm-cov
(–O2)



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  |  Branch (1068:39): [True: 0, False: 5]
  ------------------
```

`drivers/firmware/dmi_scan.c:dmi_get_date`

More examples: missing branch outcomes

gcov
(–O2)

?

```
        5: 1068:    if (s == e || *e != '/' || !month || month > 12) {
branch  0 taken 5 (fallthrough)
branch  1 taken 0
branch  2 taken 5 (fallthrough)
branch  3 taken 0
branch  4 taken 0 (fallthrough)
branch  5 taken 5
```

llvm-cov
(–O2)

```
 1068|      5|  if (s == e || *e != '/' || !month || month > 12) {
------------------
|  Branch (1068:6): [True: 0, False: 5]
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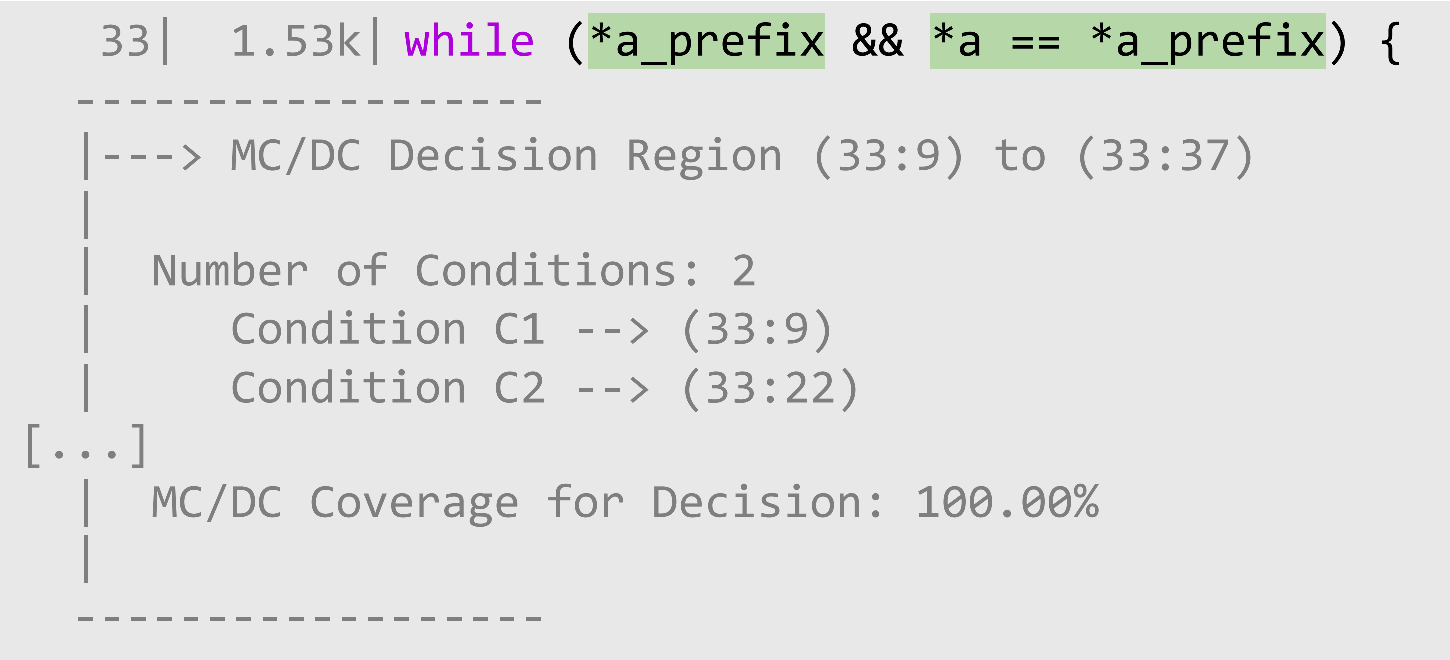
drivers/firmware/dmi_scan.c:dmi_get_date

More examples: MC/DC

gcov
(-O2)

llvm-cov
(-O2)



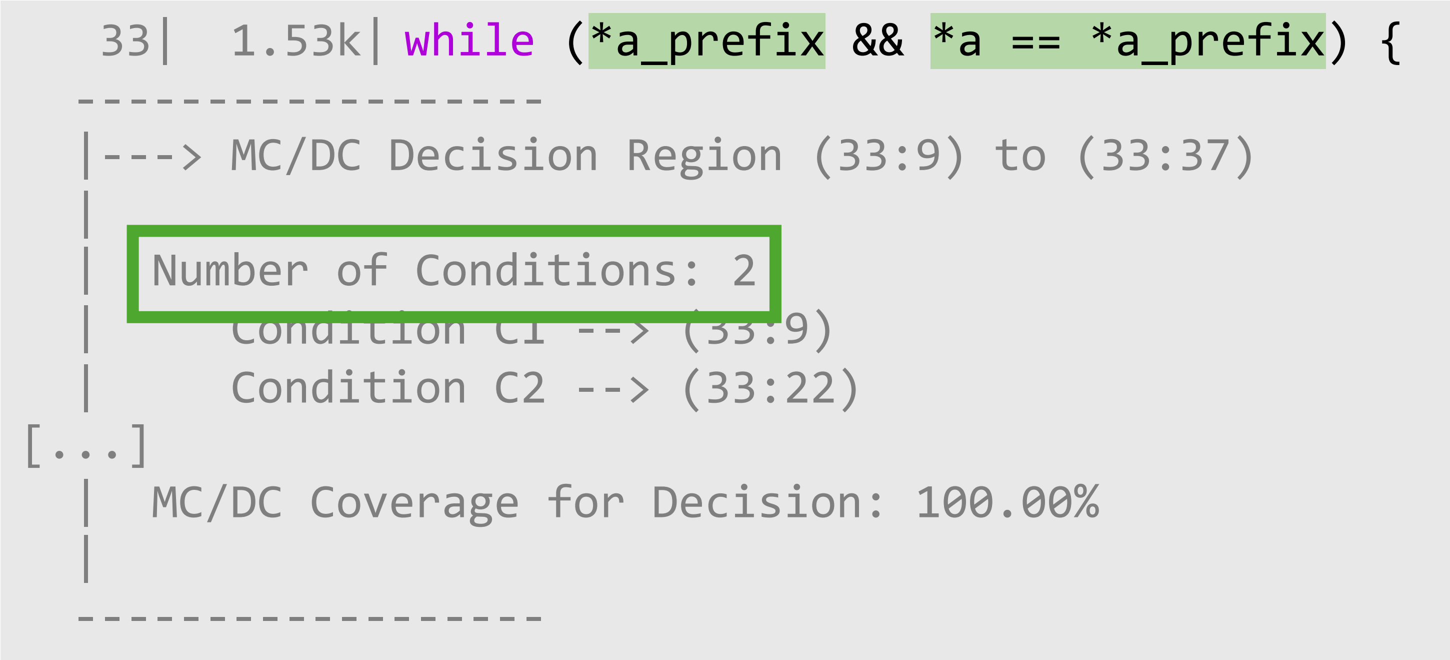
```
    33|  1.53k|while (*a_prefix && *a == *a_prefix) {
  ------------------
  |---> MC/DC Decision Region (33:9) to (33:37)
  |
  |  Number of Conditions: 2
  |     Condition C1 --> (33:9)
  |     Condition C2 --> (33:22)
[...]
  |  MC/DC Coverage for Decision: 100.00%
  |
  ------------------
```

fs/xattr.c:strcmp_prefix

More examples: MC/DC

gcov
(-O2)

llvm-cov
(-O2)



```
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  ------------------
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  |
  ------------------
```

fs/xattr.c:strcmp_prefix

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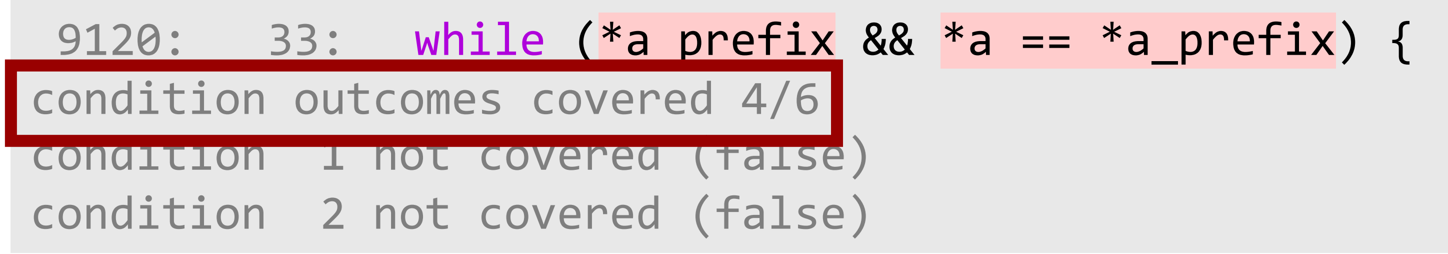
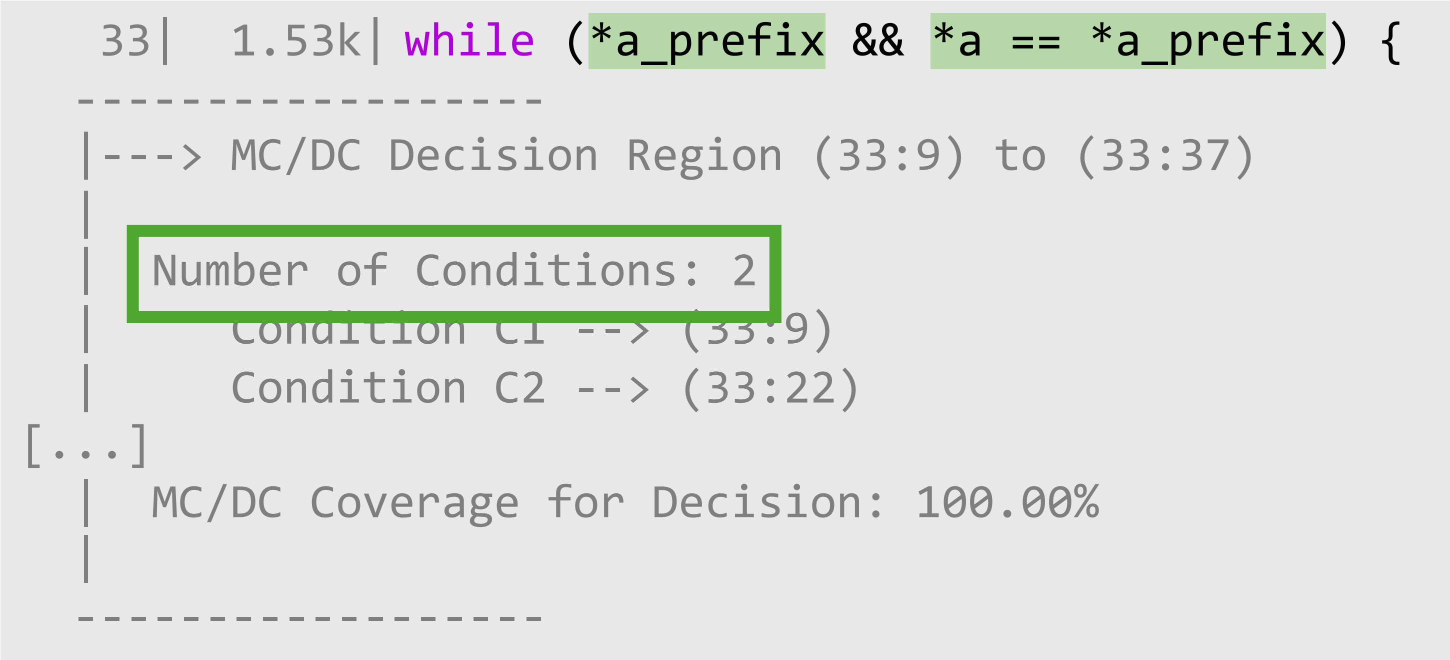
gcov
(–O2)



```
 9120:    33:   while (*a_prefix && *a == *a_prefix) {
condition outcomes covered 4/6
condition  1 not covered (false)
condition  2 not covered (false)
```

llvm-cov
(–O2)



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Proposal of `kernel/llvm-cov/`

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- Source-based code coverage of Linux kernel

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- Patches (v2)
  - [1/4] llvm-cov: add Clang's Source-based Code Coverage support
  - [2/4] llvm-cov: add Clang's MC/DC support
  - [3/4] x86: disable llvm-cov instrumentation
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Proposal of `kernel/llvm-cov/`

- Source-based code coverage of Linux kernel
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  - [3/4] x86: disable llvm-cov instrumentation
  - [4/4] x86: enable llvm-cov support
- CI demo https://github.com/xlab-uiuc/linux-mcdc

Patch implementation

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- Kbuild support

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  - `CONFIG_LLVM_COV_KERNEL`
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[2] https://lore.kernel.org/lkml/20210407211704.367039-1-morbo@google.com/

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  - With different goals: performance optimization vs. **precise coverage** for high assurance

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Steps of measuring source-based kernel coverage

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Recap: `llvm-cov` usage in user space

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$ clang -fprofile-instr-generate -fcoverage-mapping foo.c -o foo
$ LLVM_PROFILE_FILE=foo.profraw ./foo # Run the code and tests
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```

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$ # Build and instrument the kernel
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⇨

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```
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```

```
$ # Generate coverage reports
$ cp /sys/kernel/debug/llvm-cov/profraw vmlinux.profraw
$ llvm-profdata merge vmlinux.profraw -o vmlinux.profdata
$ llvm-cov show ./vmlinux -instr-profile=vmlinux.profdata
```

Recap: `llvm-cov` usage in user space

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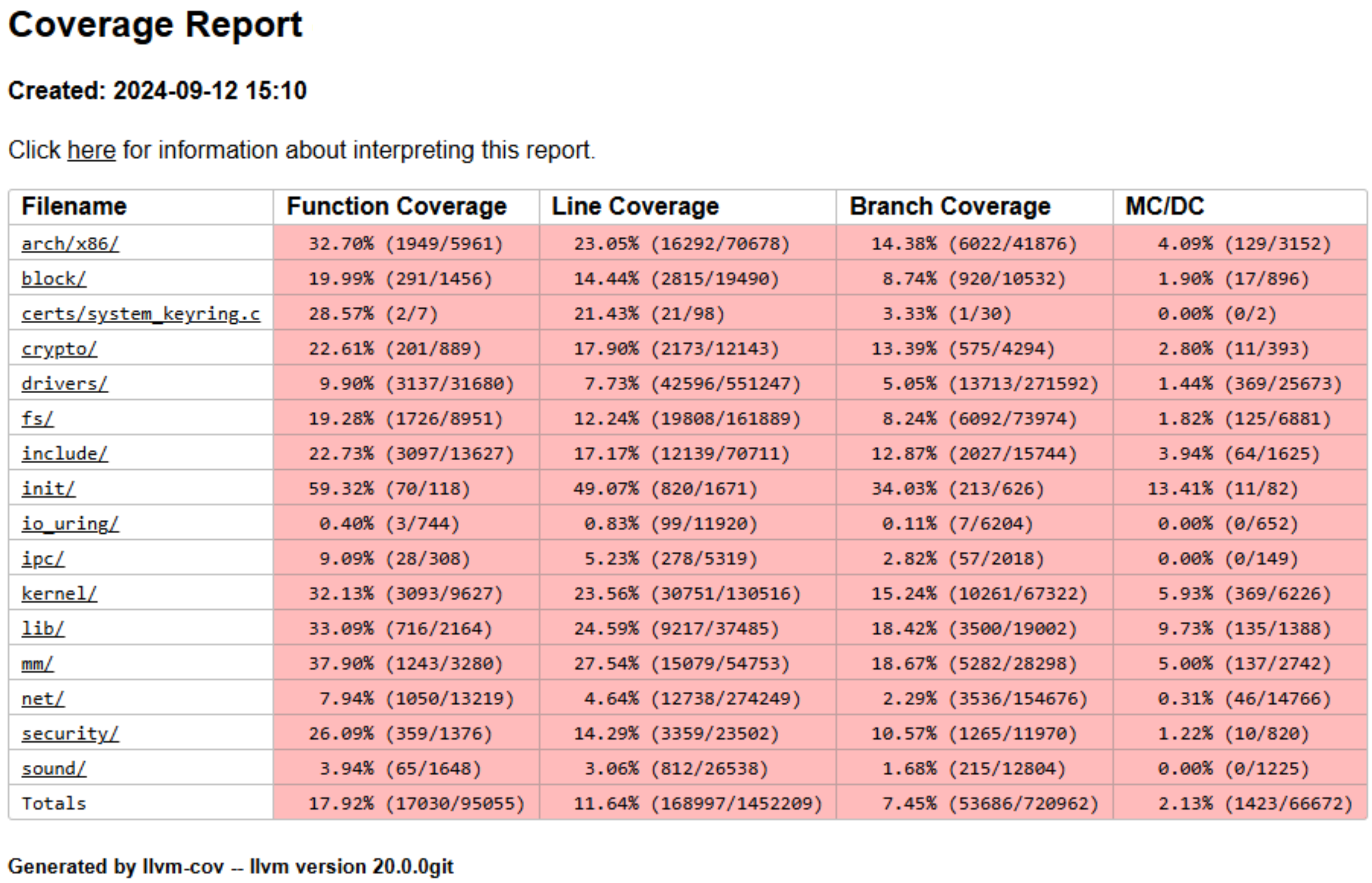
Example coverage report for KUnit tests



Coverage Report

Created: 2024-09-12 15:10

Click here for information about interpreting this report.

Filename	Function Coverage	Line Coverage	Branch Coverage	MC/DC
arch/x86/	32.70% (1949/5961)	23.05% (16292/70678)	14.38% (6022/41876)	4.09% (129/3152)
block/	19.99% (291/1456)	14.44% (2815/19490)	8.74% (920/10532)	1.90% (17/896)
certs/system_keyring.c	28.57% (2/7)	21.43% (21/98)	3.33% (1/30)	0.00% (0/2)
crypto/	22.61% (201/889)	17.90% (2173/12143)	13.39% (575/4294)	2.80% (11/393)
drivers/	9.90% (3137/31680)	7.73% (42596/551247)	5.05% (13713/271592)	1.44% (369/25673)
fs/	19.28% (1726/8951)	12.24% (19808/161889)	8.24% (6092/73974)	1.82% (125/6881)
include/	22.73% (3097/13627)	17.17% (12139/70711)	12.87% (2027/15744)	3.94% (64/1625)
init/	59.32% (70/118)	49.07% (820/1671)	34.03% (213/626)	13.41% (11/82)
io_uring/	0.40% (3/744)	0.83% (99/11920)	0.11% (7/6204)	0.00% (0/652)
ipc/	9.09% (28/308)	5.23% (278/5319)	2.82% (57/2018)	0.00% (0/149)
kernel/	32.13% (3093/9627)	23.56% (30751/130516)	15.24% (10261/67322)	5.93% (369/6226)
lib/	33.09% (716/2164)	24.59% (9217/37485)	18.42% (3500/19002)	9.73% (135/1388)
mm/	37.90% (1243/3280)	27.54% (15079/54753)	18.67% (5282/28298)	5.00% (137/2742)
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security/	26.09% (359/1376)	14.29% (3359/23502)	10.57% (1265/11970)	1.22% (10/820)
sound/	3.94% (65/1648)	3.06% (812/26538)	1.68% (215/12804)	0.00% (0/1225)
Totals	17.92% (17030/95055)	11.64% (168997/1452209)	7.45% (53686/720962)	2.13% (1423/66672)

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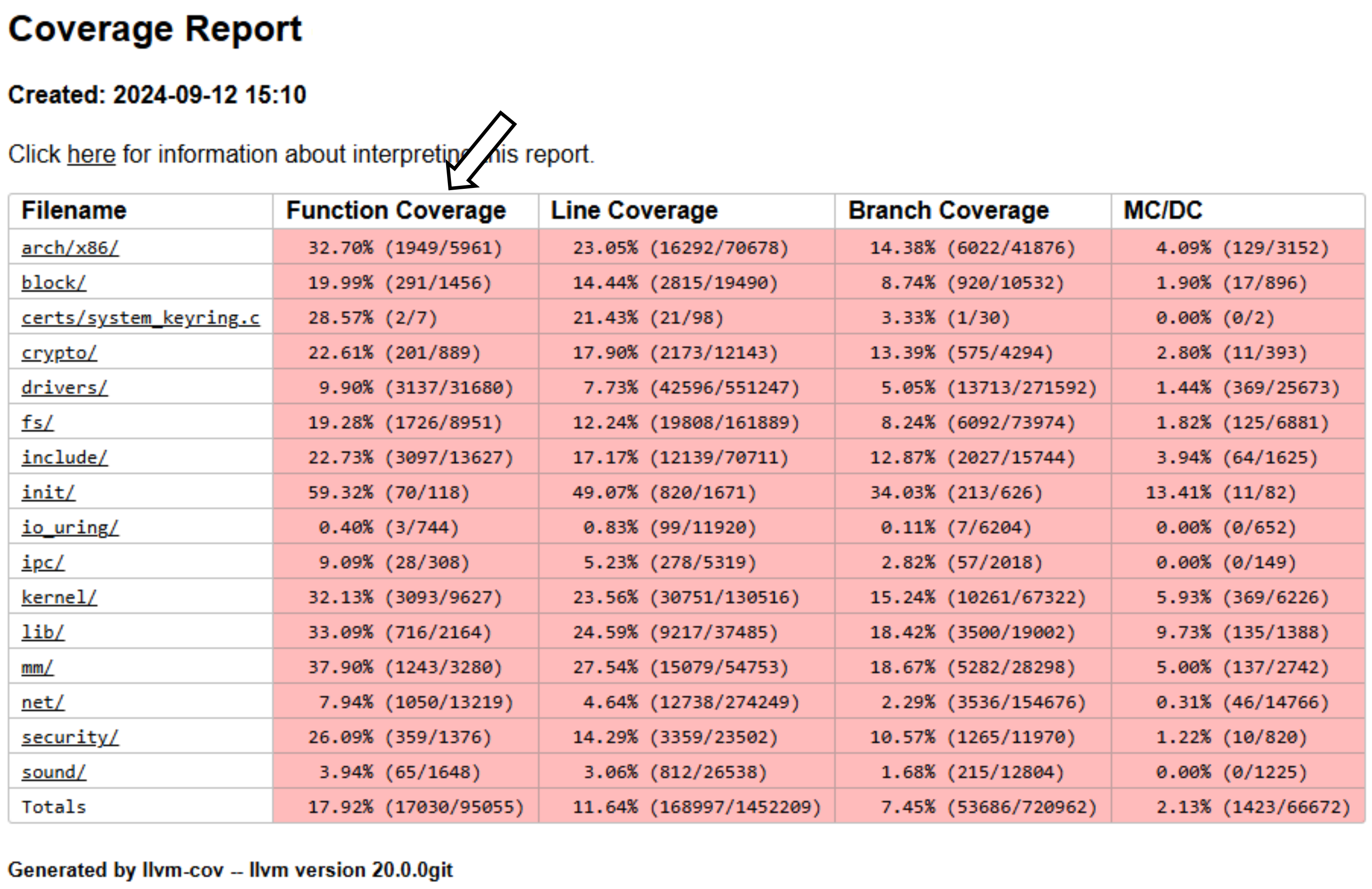
Summary page

Example coverage report for KUnit tests



Coverage Report

Created: 2024-09-12 15:10

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Filename	Function Coverage	Line Coverage	Branch Coverage	MC/DC
arch/x86/	32.70% (1949/5961)	23.05% (16292/70678)	14.38% (6022/41876)	4.09% (129/3152)
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fs/	19.28% (1726/8951)	12.24% (19808/161889)	8.24% (6092/73974)	1.82% (125/6881)
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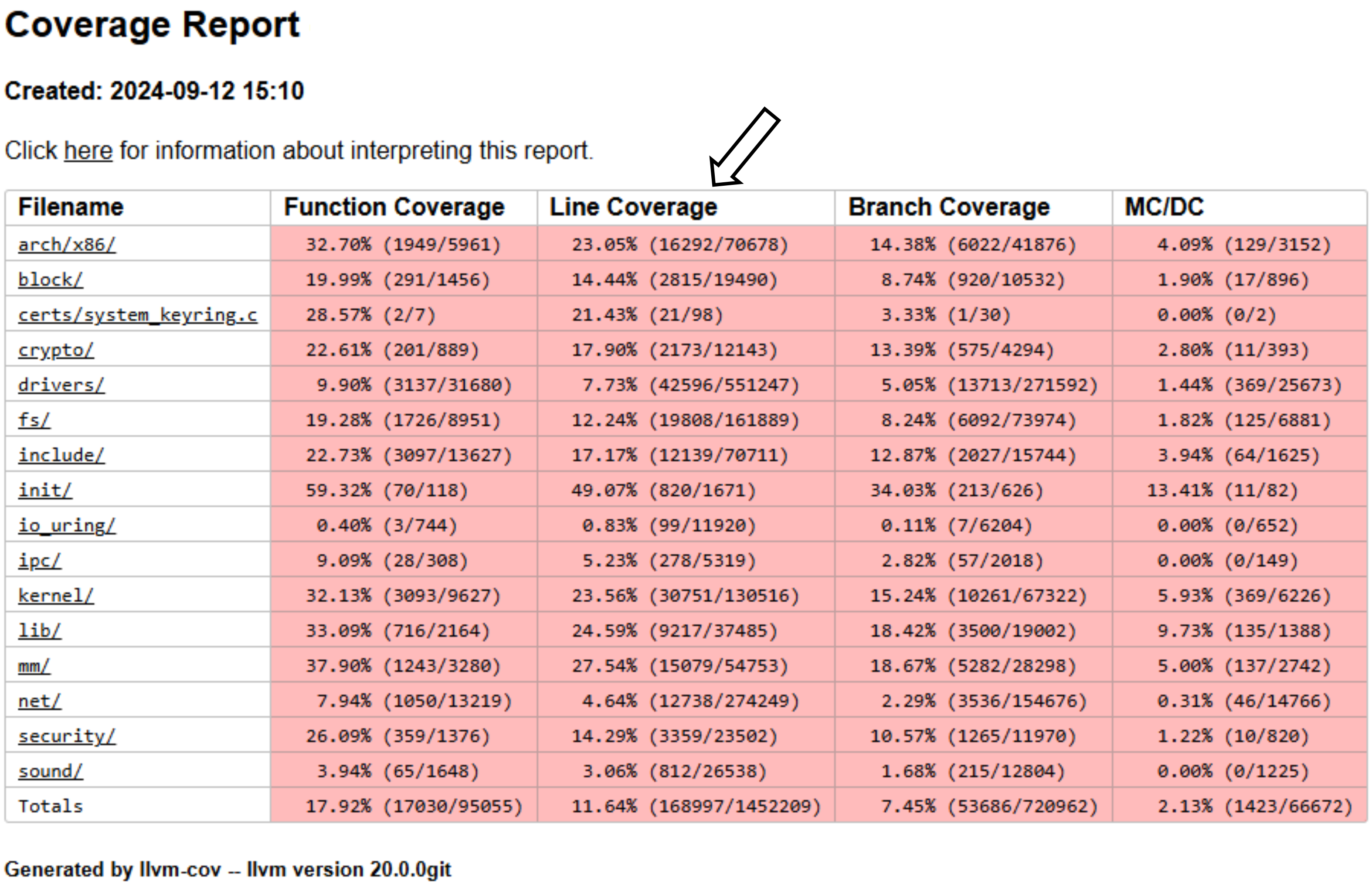
Summary page

Example coverage report for KUnit tests



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Summary page

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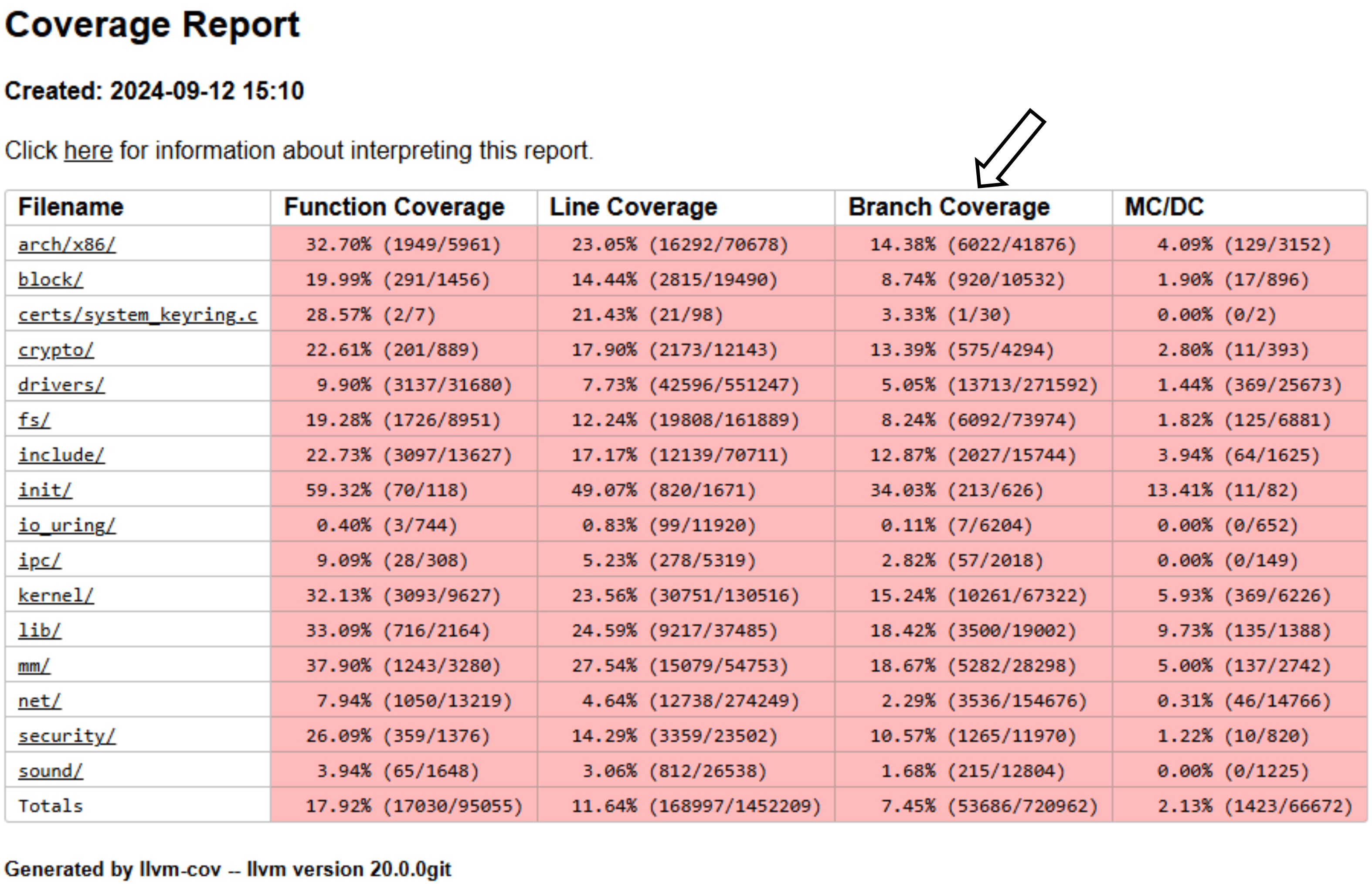

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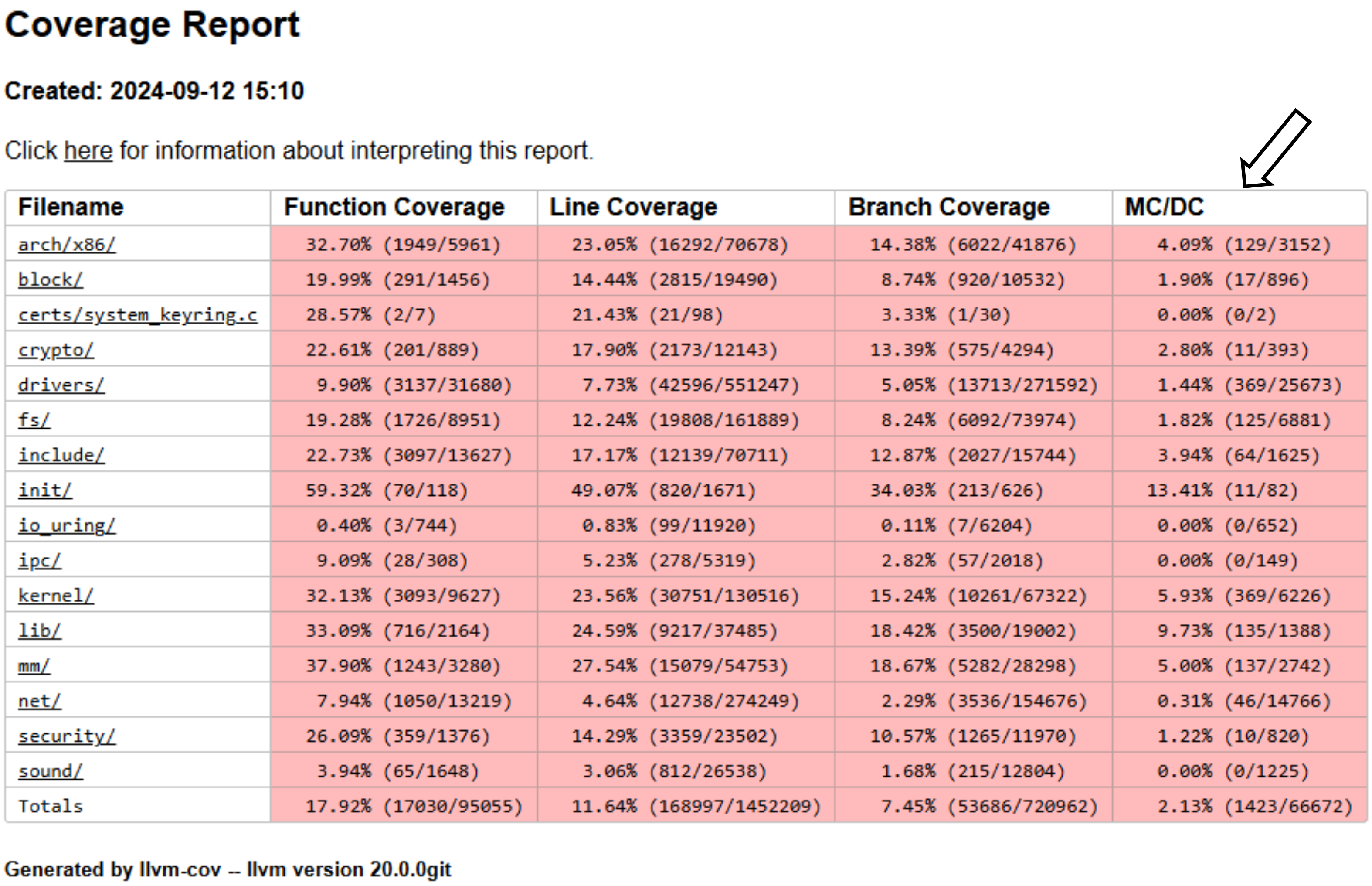
Summary page

Example coverage report for KUnit tests



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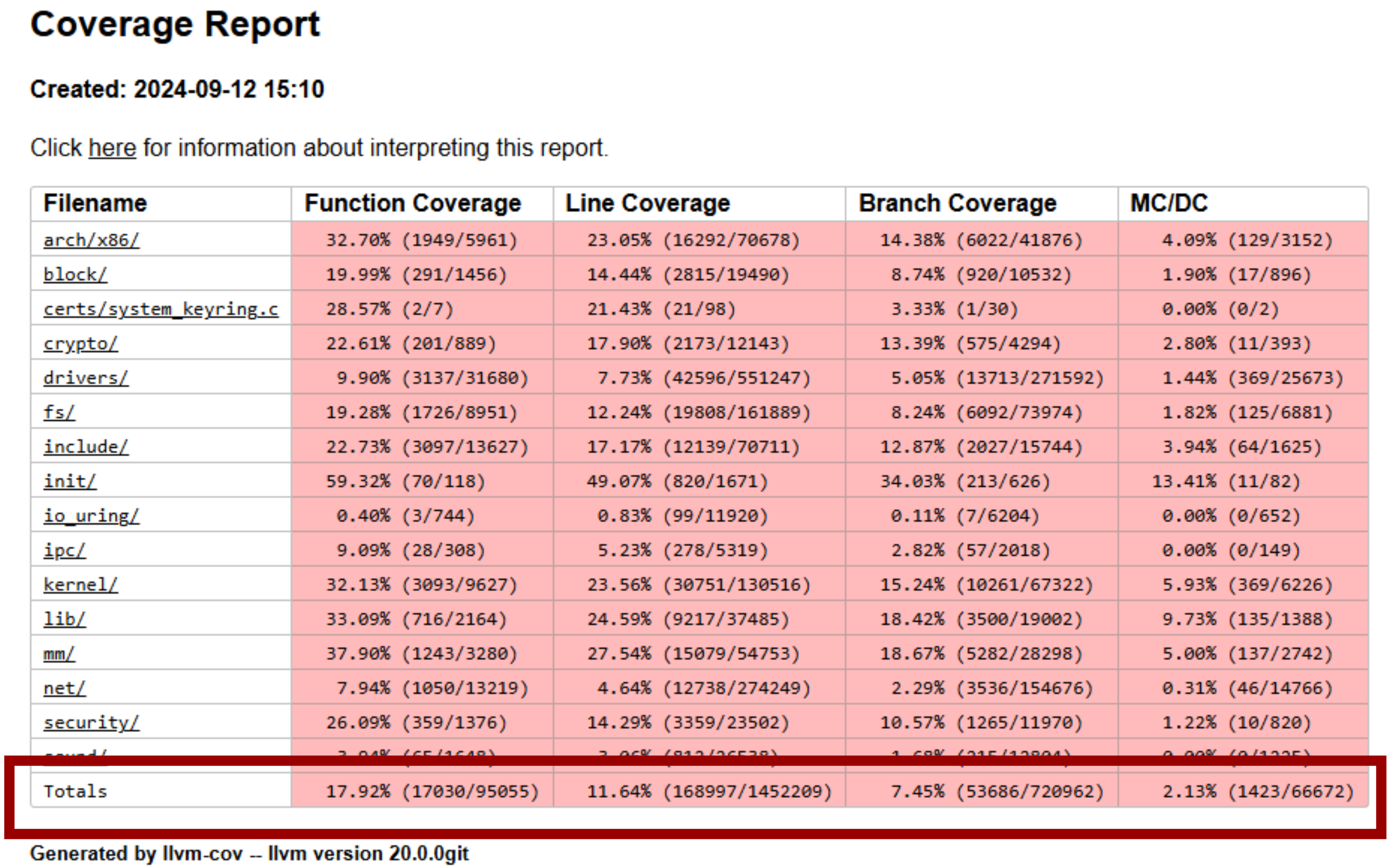
Summary page

Example coverage report for KUnit tests



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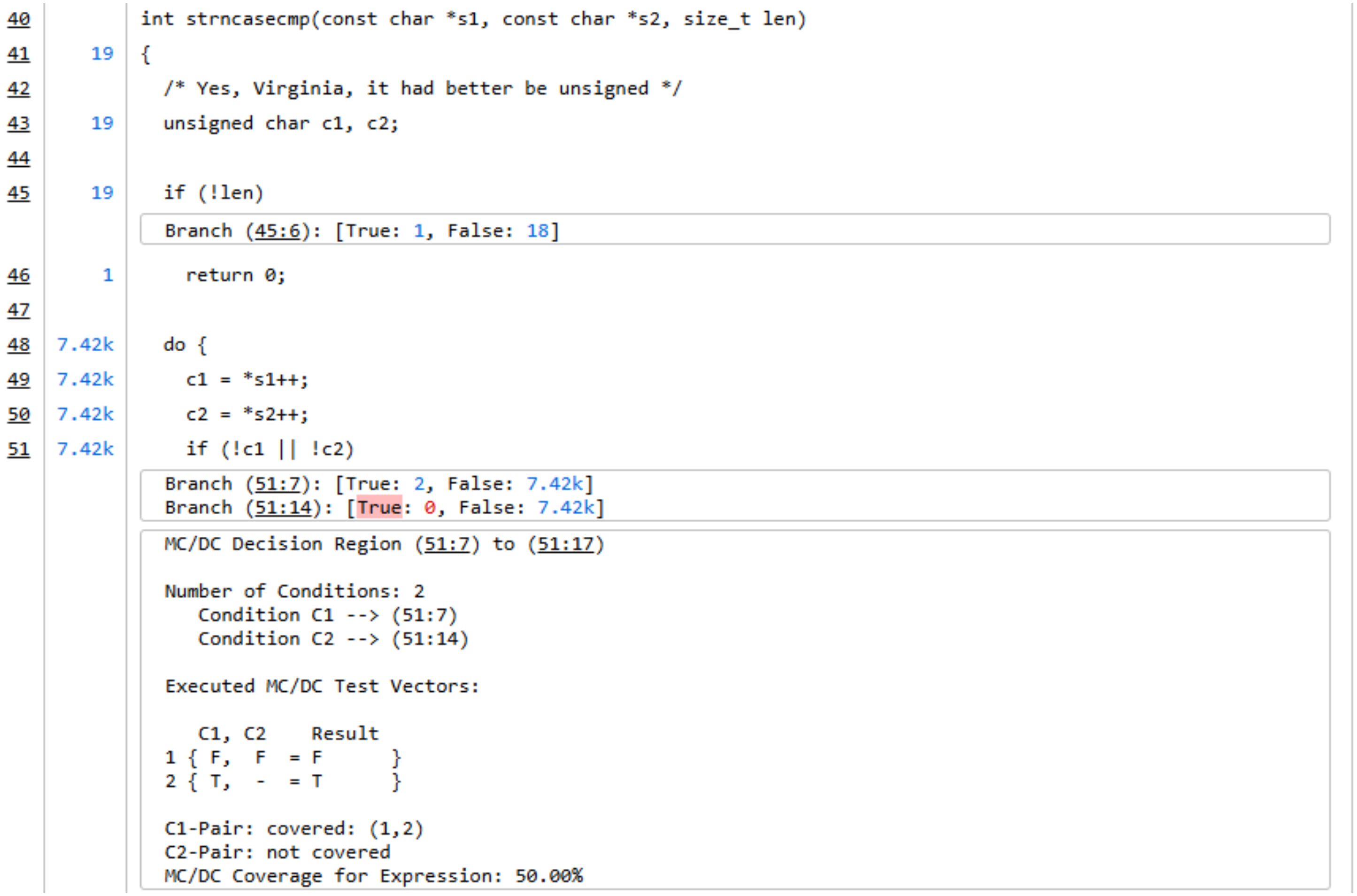
Summary page

Example coverage report for KUnit tests



```
40          int strncasecmp(const char *s1, const char *s2, size_t len)
41      19  {
42            /* Yes, Virginia, it had better be unsigned */
43      19    unsigned char c1, c2;
44
45      19    if (!len)
            Branch (45:6): [True: 1, False: 18]

46       1      return 0;
47
48   7.42k    do {
49   7.42k      c1 = *s1++;
50   7.42k      c2 = *s2++;
51   7.42k      if (!c1 || !c2)
            Branch (51:7): [True: 2, False: 7.42k]
            Branch (51:14): [True: 0, False: 7.42k]

            MC/DC Decision Region (51:7) to (51:17)

            Number of Conditions: 2
               Condition C1 --> (51:7)
               Condition C2 --> (51:14)

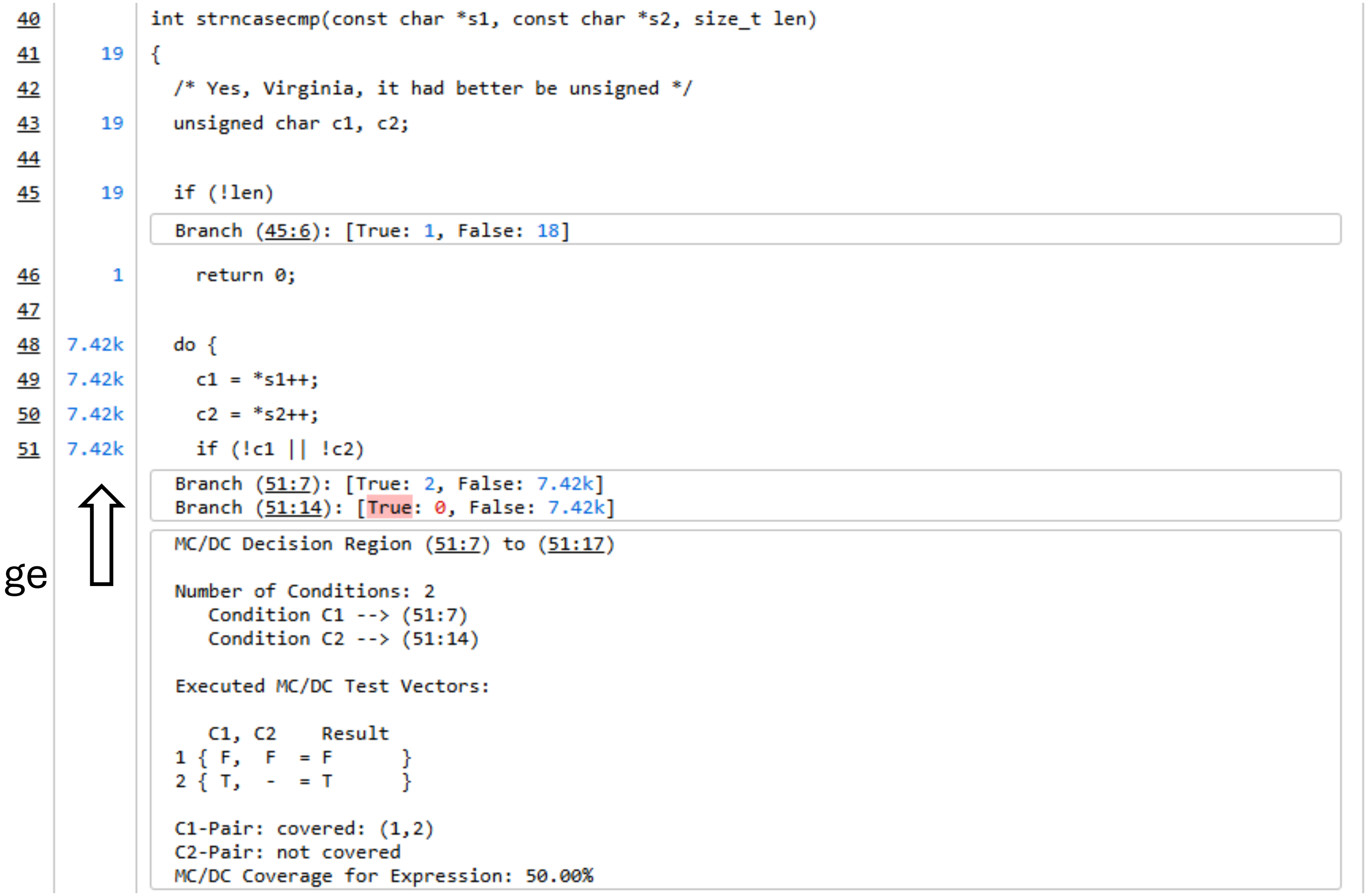
            Executed MC/DC Test Vectors:

               C1, C2    Result
            1 { F,  F  = F      }
            2 { T,  -  = T      }

            C1-Pair: covered: (1,2)
            C2-Pair: not covered
            MC/DC Coverage for Expression: 50.00%
```

`lib/string.c` (tested by `string_kunit.c`)

Example coverage report for KUnit tests



```
40          int strncasecmp(const char *s1, const char *s2, size_t len)
41      19  {
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              Branch (51:14): [True: 0, False: 7.42k]

              MC/DC Decision Region (51:7) to (51:17)

              Number of Conditions: 2
                 Condition C1 --> (51:7)
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              Executed MC/DC Test Vectors:

                 C1, C2    Result
              1 { F,  F   = F      }
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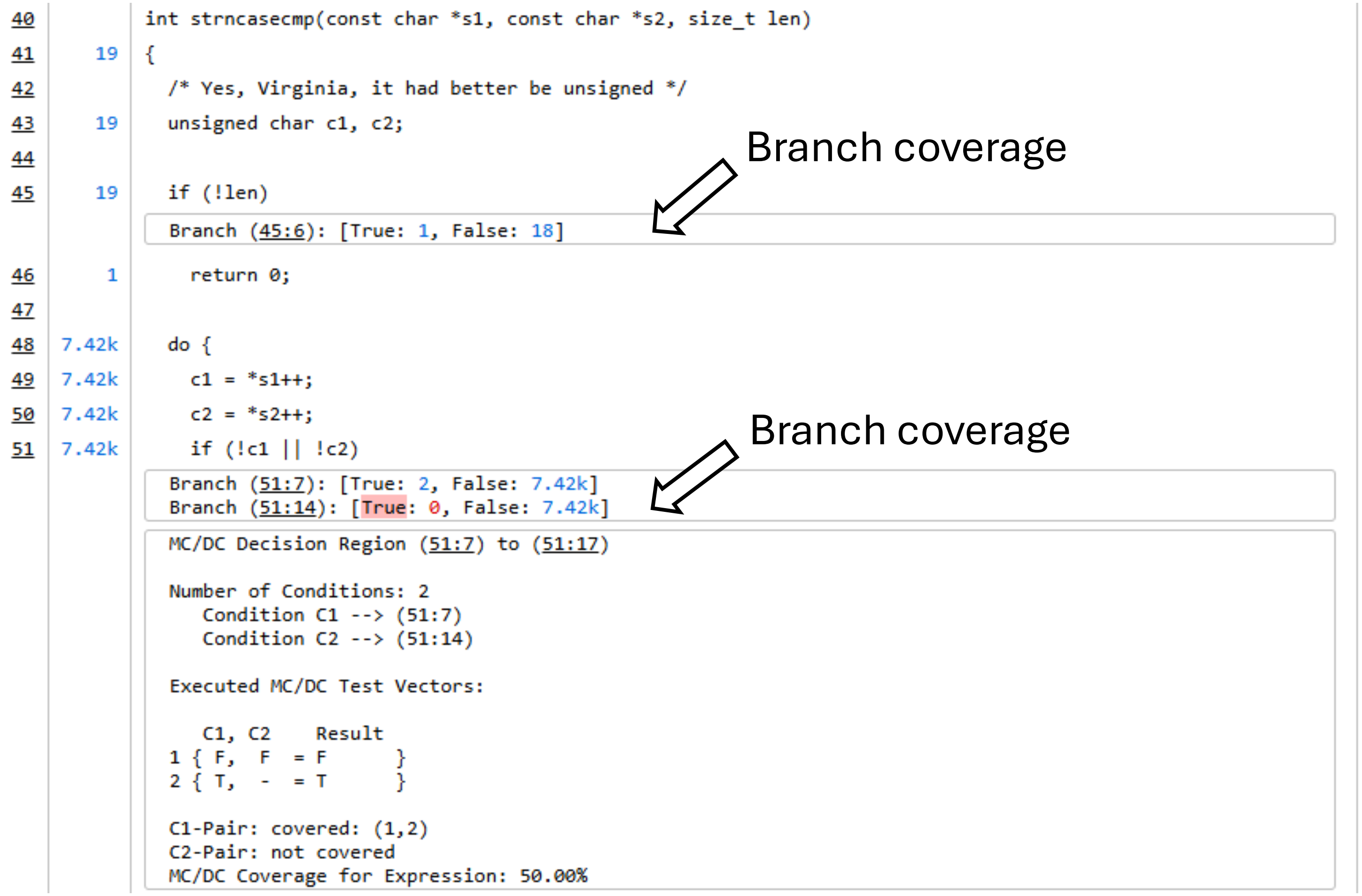
              MC/DC Coverage for Expression: 50.00%
```

Line coverage

`lib/string.c` (tested by `string_kunit.c`)

Example coverage report for KUnit tests



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40          int strncasecmp(const char *s1, const char *s2, size_t len)
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              Branch (51:7): [True: 2, False: 7.42k]
              Branch (51:14): [True: 0, False: 7.42k]
              MC/DC Decision Region (51:7) to (51:17)

              Number of Conditions: 2
                 Condition C1 --> (51:7)
                 Condition C2 --> (51:14)

              Executed MC/DC Test Vectors:

                 C1, C2    Result
              1 { F,  F  = F      }
              2 { T,  -  = T      }

              C1-Pair: covered: (1,2)
              C2-Pair: not covered
              MC/DC Coverage for Expression: 50.00%
```

Branch coverage

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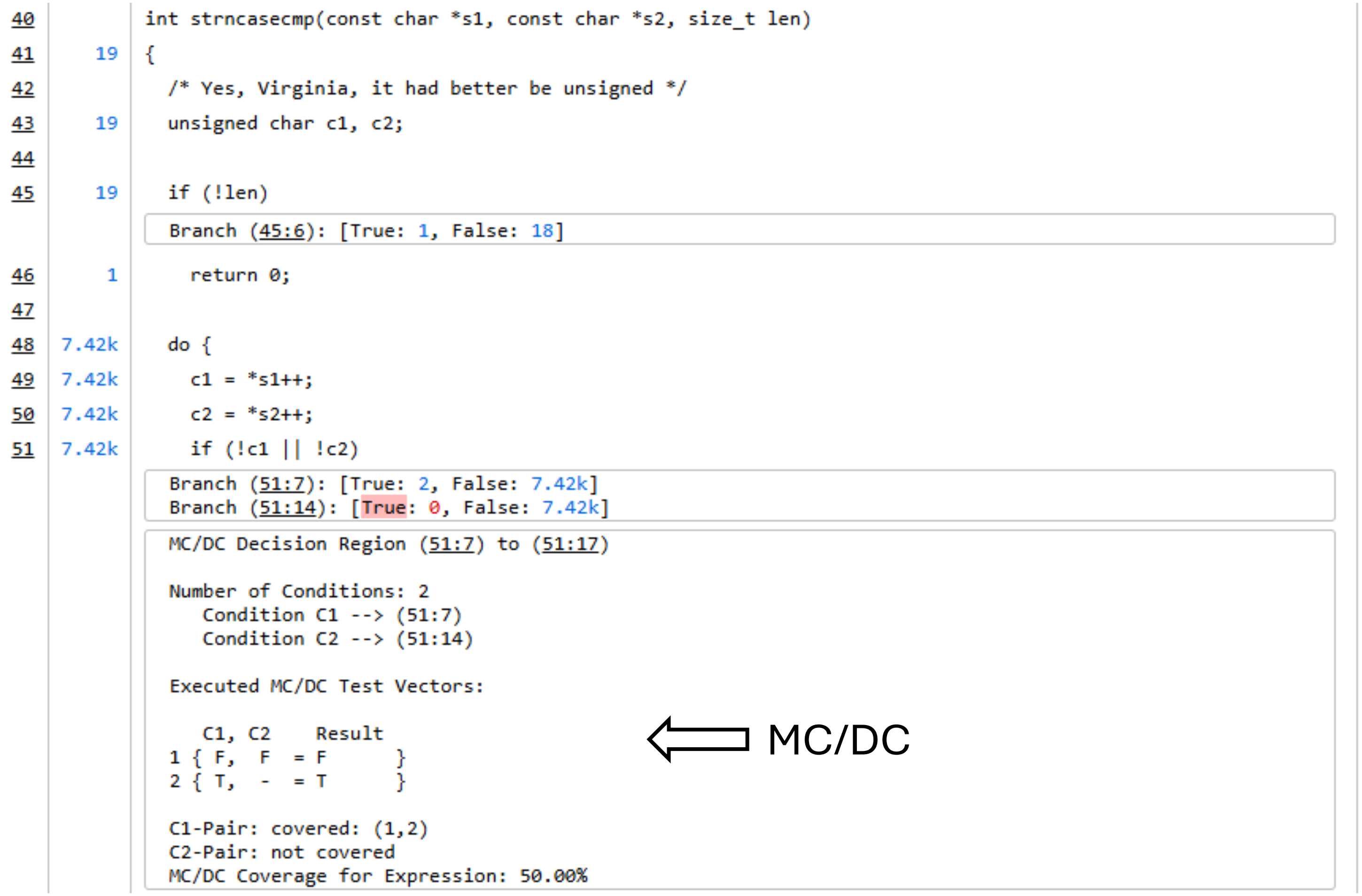
`lib/string.c` (tested by `string_kunit.c`)

Example coverage report for KUnit tests



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40          int strncasecmp(const char *s1, const char *s2, size_t len)
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              Branch (51:7): [True: 2, False: 7.42k]
              Branch (51:14): [True: 0, False: 7.42k]
              MC/DC Decision Region (51:7) to (51:17)

              Number of Conditions: 2
                 Condition C1 --> (51:7)
                 Condition C2 --> (51:14)

              Executed MC/DC Test Vectors:

                 C1, C2    Result
              1 { F,  F  = F      }
              2 { T,  -  = T      }

              C1-Pair: covered: (1,2)
              C2-Pair: not covered
              MC/DC Coverage for Expression: 50.00%
```

MC/DC

`lib/string.c` (tested by `string_kunit.c`)

Known limitations

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    - Modify LLVM inlining passes
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  - Potential alleviations
    - Separate information needed online and offline [3,4]

[3] https://discourse.llvm.org/t/instrprofiling-lightweight-instrumentation/59113
[4] https://discourse.llvm.org/t/rfc-add-binary-profile-correlation-to-not-load-profile-metadata-sections-into-memory-at-runtime/74565

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[5] https://discourse.llvm.org/t/rfc-single-byte-counters-for-source-based-code-coverage/75685

Known limitations (MC/DC-specific)

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  - Can only be solved in LLVM upstream

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- Precise **source-based coverage** produces more informative reports
- Propose **`kernel/llvm-cov/`** for unique insights into kernel codebase to testers, developers and certificate applicants
  - It can coexist with gcov and KCOV
- Request for comments
  - LKML archive: https://lore.kernel.org/lkml/20240824230641.385839-1-wentaoz5@illinois.edu/
  - CI demo: https://github.com/xlab-uiuc/linux-mcdc

Backup slides for discussions

Feedback in LKML

- (Thomas Gleixner) Unifying `Makefile` variables `*COV_PROFILE`
  - Each `*cov` is implemented in different ways and separate lists are needed
- (Peter Zijlstra) `noinstr` attribute
  - It is correctly respected by the current toolchain

Old PGO debates

- https://lore.kernel.org/lkml/202106281231.E99B92BB13@keescook/
- Instrumentation (for precise coverage) vs. sampling (for profiling)
  - `perf` is not complete for coverage measurement, also hard to map back to source code

`syzkaller` discussion thread

- https://groups.google.com/g/syzkaller/c/JLX7ivDED5o
- Reuse `KCOV` interface
  - Needs compiler changes
- Measure coverage for specific processes (e.g. tests issued from user space) vs. overall execution

Future plan

- Support more architectures
- (Chuck Wolber) update LLVM intrinsics for more precise timing control

More backup slides

Backup: KCOV community is seeing similar problems

We find the current llvm coverage confusing as well (in the context of syzkaller/syzbot)

- Syzkaller mailing list discussion https://groups.google.com/g/syzkaller/c/JLX7ivDED5o
- One future work direction: per-test coverage

Backup: complete quote from LLVM docs

LLVM optimizations (such as inlining or CFG simplification) should have no impact on coverage report quality. This is due to the fact that the mapping from source regions to profile counters is immutable, and is generated before the LLVM optimizer kicks in. The optimizer can’t prove that profile counter instrumentation is safe to delete (because it’s not: it affects the profile the program emits), and so leaves it alone.

Note that this coverage feature does not rely on information that can degrade during the course of optimization, such as debug info line tables.

[1] https://clang.llvm.org/docs/SourceBasedCodeCoverage.html#impact-of-llvm-optimizations-on-coverage-reports

Backup: quote from `syzkaller` docs

Coverage is based on tracing coverage points inserted into the object code by the compiler. A coverage point generally refers to a basic block of code or a CFG edge (this depends on the compiler and instrumentation mode used during build, e.g. for Linux and clang the default mode is CFG edges, while for gcc the default mode is basic blocks). Note that coverage points are inserted by the compiler in the middle-end after a significant number of transformation and optimization passes. As the result coverage may poorly relate to the source code. For example, you may see a covered line after a non-covered line, or you may not see a coverage point where you would expect to see it, or vice versa (this may happen if the compiler splits basic blocks, or turns control flow constructs into conditional moves without control flow, etc). Assessing coverage is still generally very useful and allows to understand overall fuzzing progress, but treat it with a grain of salt.

https://github.com/google/syzkaller/blob/master/docs/coverage.md

Backup: steps to reproduce these `gcov` examples

- https://github.com/xlab-uiuc/linux-mcdc/issues/7

Backup: full-kernel instrumentation overhead

- Machine: PowerEdge R650 (kindly provided by CloudLab)
  - CPU: Two 36-core Intel Xeon Platinum 8360Y at 2.4GHz
  - RAM: 256GB ECC Memory (16x 16 GB 3200MHz DDR4)
- Clang: snapshot 20240917071600
  - For "apple-to-apple" comparison, here `gcov` is indeed Clang's `gcov` compatible mode, without MC/DC
- QEMU/KVM

	Build time	**`vmlinux` size**	**Boot time**	**Boot time w/ KUnit**
`noinstr`	53s	53M	2.25s	7.34s
`gcov`	1m10s	79M	2.40s	8.64s
`llvm-cov`	12m26s	1.3G	2.68s	9.80s