MC/DC for Space

A new Approach to Ensure MC/DC Structural Coverage with Exclusively Open Source Tools

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Motivation

How many tests do we need for the following code?

- 1 statement
- How many branches?
- How many decisions?
- 1, 2, 3, 4 tests?

```c
#include <stdbool.h>

bool test(bool a, bool b, bool c)
{
        return b && c || a;
}
```

Current Approach to MC/DC

- **MC/DC** is a popular **structural coverage** metric required by many standards, e.g., DO-178.
- It is a **demanding metric** as it requires **many more tests** than branch/decision coverage.
- Its assessment is usually done with **proprietary tools** and **late in the project**.

MC/DC as an ECSS Requirement

- Definition in E-ST-40 §3.2.18
- MC/DC is one of the structural coverage requirements of ECSS E-ST-40 (§5.8.3.5.b), Q-ST-80 (§6.3.5.2), and Q-HB-80-04 (Table 5-3):
  - the coverage percentage must be agreed for all categories except CAT A

    →Often the agreement means 0% for Cat B and lower
  - the assessment is to be done on the source code
  - the coverage must be achieved by unit, integration, and validation testing

MC/DC in ECSS

E-ST-40 §5.8.3.5.b

Code coverage versus criticality category	A	B	C	D
Source code statement coverage	100%	100%	AM	AM
Source code decision coverage	100%	100%	AM	AM
Source code modified condition and decision coverage	100%	AM	AM	AM
NOTE: "AM" means that the value is agreed with the customer and measured as per ECSS-Q-ST-80 clause 6.3.5.2.				

Q-HB-80-04 Table 5-3

Statement Coverage (Source Code)	1	1	1	
Statement Coverage (Object Code)	1	P.D.	P.D.	P.D.
Decision Coverage (Source Code)	1	1	1	P.D.
Modified Condition & Decision Coverage (Source Code)	1	P.D.	P.D.	P.D.

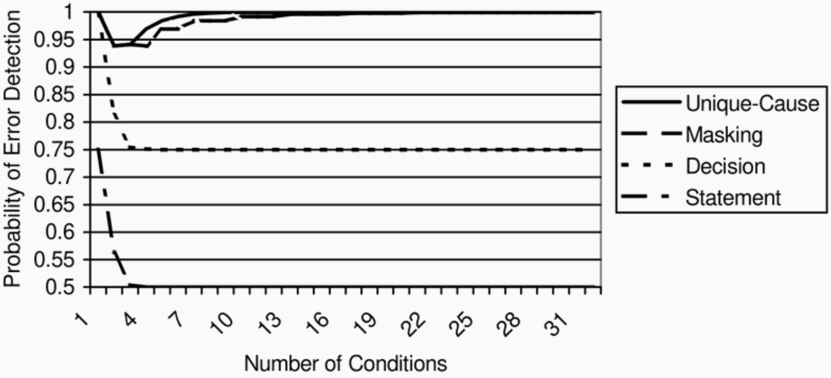


Figure 1: Minimum probability of logic error detection vs. number of conditions[1]

[1] J.J. Chilenski. "An Investigation of Three Forms of the Modified Condition Decision Coverage (MCDC) Criterion", 2001.

What's the Problem

- It is deemed that the **testing effort** is **expensive**, as it requires many more tests than simple decision coverage.
- The qualified proprietary **tools** used for the assessment are **expensive** and using them requires further effort.
- The **tools cannot be freely redistributed** within delta-qualification kits (e.g., MLFS, RTEMS SMP)

This leads to

- Trying to avoid MC/DC altogether within a project

  →Agree on 0% MC/DC
- Imposing unnatural coding rules

  →only 1 condition per decision
- Lower the MC/DC goal to make it meaningless

  →achieve 80% MC/DC

Our Goal

We propose

To produce a **method** and a **tool** that:

- Helps developers to assess the achieved MC/DC coverage
- Allows *normal* source code writing without *impractical* coding rule restrictions.
- Allows an open source based approach to ensure the free distribution of the complete unit and validation testing workflow for delta-qualification tool-kits.

Advantages of an Open Source Approach

An open source based system allows us to:

- Deploy a **Continuous Integration** system **without** long-term **licensing costs** capable of:
  - building the software
  - unit-testing the software
  - validation testing the software
  - assessing product assurance metrics including MC/DC
- **Distribute** the complete **Continuous Integration** system together with the test-suite for project specific **delta qualification**.
- Projects can benefit from this approach as commonly available open source tools will suffice for MC/DC assessment.

Necessary Concepts

For structural coverage we need:

- 1 test for statement coverage
- 2 tests for decision coverage
- 4 tests for MC/DC
- We need to show that every condition in the decision correctly contributes to the result.

```c
#include <stdbool.h>

bool test(bool a, bool b, bool c)
{
        return b && c || a;
}
```

Which Kind of MC/DC

There are several kind of MC/DC, depending on the definition:

- Unique cause MC/DC
- Unique cause + Masking MC/DC
- Masking MC/DC

Our MC/DC

We will deal here with masking MC/DC, as it is the most practical one, is the one currently used by DO-178C, and matches well with short-circuiting in the C language.

Truth table

$f(a,b,c) = b \land c \lor a$:

case	b	c	a	result
1	0	0	0	FALSE
2	0	0	1	TRUE
3	0	1	0	FALSE
4	0	1	1	TRUE
5	1	0	0	FALSE
6	1	0	1	TRUE
7	1	1	0	TRUE
8	1	1	1	TRUE

```c
#include <stdbool.h>

bool test(bool a, bool b, bool c)
{
        return b && c || a;
}
```

Truth table with masking

$f(a,b,c) = b \,\&\&\, c \,\|\, a$:

case	b	c	a	result
1	0	?	0	FALSE
2	0	?	1	TRUE
3	0	?	0	FALSE
4	0	?	1	TRUE
5	1	0	0	FALSE
6	1	0	1	TRUE
7	1	1	?	TRUE
8	1	1	?	TRUE

```c
#include <stdbool.h>

bool test(bool a, bool b, bool c)
{
        return b && c || a;
}
```

MC/DC for our Example

Truth table with masking

$f(a, b, c) = b \;\&\&\; c \;||\; a$:

case	b	c	a	result
1	0	?	0	FALSE
2	0	?	1	TRUE
3	0	?	0	FALSE
4	0	?	1	TRUE
5	1	0	0	FALSE
6	1	0	1	TRUE
7	1	1	?	TRUE
8	1	1	?	TRUE

Test pairs:

- to test **b** with independence: $\{1, 7\}$
- to test **c** with independence: $\{5, 7\}$
- to test **a** with independence: $\{5, 6\}$

Thus, we can take cases: $\{1, 5, 6, 7\}$ to achieve full MC/DC

Assessing Structural Coverage with gcov

The free tool gcov shows us:

- Full statement and branch coverage with cases: $\{1, 6, 7\}$
- 3 test cases are enough:
  - 1 more than decision coverage
  - 1 less than MC/DC
- The 6 covered branches are called OBC: Object Branch Coverage

```
  Branch data       Line data    Source code
                  :            : #include <stdbool.h>
                  :            :
                  :          3 : bool test(bool a, bool b, bool c) {
[ +  +  +  +      :          3 :     return (b && c) || a;
         +  + ]
                  :            : }
                  :            :
                  :          1 : int main() {
                  :          1 :     test(true, true, false);
                  :          1 :     test(false, true, true);
                  :          1 :     test(false, false, false);
                  :          1 :     return 0;
                  :            : }
```

gcov by itself is not enough

gcov alone does not show if full MC/DC is achieved even if it requires more than just decision coverage.

Assembler vs. AST vs. BDD

```
        ld      [%fp+72], %g1
        cmp     %g1, 0
        be      .LL2
         nop
```
Basic Block to check 'b'.

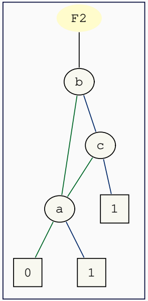
```
        ld      [%fp+76], %g1
        cmp     %g1, 0
        bne     .LL3
         nop
```
Basic Block to check 'c'

```
.LL2:
        ld      [%fp+68], %g1
        cmp     %g1, 0
        be      .LL4
         nop
```
Basic Block to check 'a'

```
.LL3:
        mov     1, %g1
        b       .LL5
         nop
```
Return 1

```
.LL4:
        mov     0, %g1
```
Return 0

```
.LL5:
        and     %g1, 0xff, %g1
```




```
`-CompoundStmt 0x55e01c847df8 <line:5:1, line:7:1>
  `-ReturnStmt 0x55e01c847de8 <line:6:2, col:19>
    `-BinaryOperator 0x55e01c847dc8 <col:9, col:19> 'int' '||'
      |-BinaryOperator 0x55e01c840480 <col:9, col:14> 'int' '&&'
      | |-ImplicitCastExpr 0x55e01c840450 <col:9> 'int' <LValueToRValue>
      | | `-DeclRefExpr 0x55e01c840410 <col:9> 'int' lvalue ParmVar 0x55e01c8401a0 'b' 'int'
      | `-ImplicitCastExpr 0x55e01c840468 <col:14> 'int' <LValueToRValue>
      |   `-DeclRefExpr 0x55e01c840430 <col:14> 'int' lvalue ParmVar 0x55e01c840220 'c' 'int'
      `-ImplicitCastExpr 0x55e01c847db0 <col:19> 'int' <LValueToRValue>
        `-DeclRefExpr 0x55e01c847d90 <col:19> 'int' lvalue ParmVar 0x55e01c840120 'a' 'int'
```

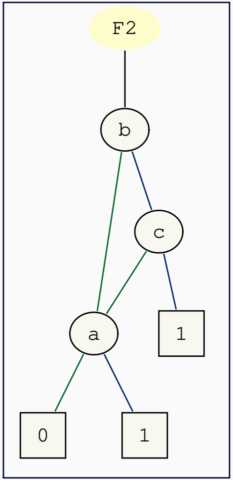
Our Method and Tool

For our example function $f(a, b, c) = b \, \&\& \, c \, || \, a$:

- The compiler generates a BDD (Binary Decision Diagram) in object code when invoked without optimization (-O0)
- The BDD has 6 edges

  as the OBC branches count in gcov
- The BDD has 3 paths/endpoints

  as the tests needed to cover 100% in gcov



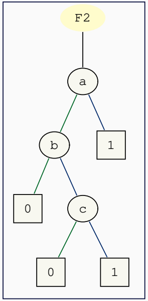
From OBC to MC/DC

If we transform our example function to $f(a, b, c) = a \mathbin{||} b \mathbin{\&\&} c$:

- The BDD has 6 edges

  as the OBC branches count in gcov
- The BDD has 4 paths/endpoints

  as the tests needed to achieve MC/DC



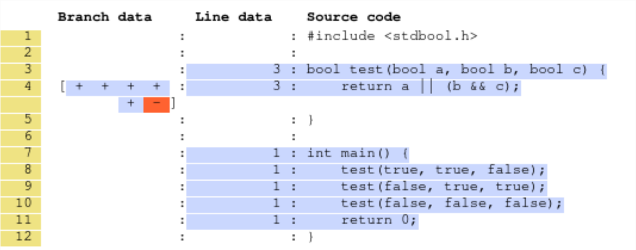
Treelike BDDs show MC/DC

For **treelike BDDs** it is **proven**[2] that **OBC** implies **MC/DC** and gcov is able to show this.

[2] Comar, Guitton, Hainque, and Quinot. "Formalization and Comparison of MCDC and Object Branch Coverage Criteria," 2011.

The free tool gcov shows us:

- Full statement but incomplete object branch coverage with cases: $\{1, 6, 7\}$
- 3 test cases are **not** enough:
  - 2 more than decision coverage are required now
  - This is proven to be equivalent to MC/DC
- One test case ($\{5\}$ true, false, false) is missing to achieve 100% MC/DC



Our Tool

Features of our tool:

- Enables us to assess all decisions in C
- Detects decisions with non-treelike BDDs
- Proposes reordering to achieve a treelike BDD
- Enables the MC/DC assessment with gcov
- Python and clang based
- Makes use of the clang AST (Abstract Syntax Tree)

```
$ python3 mcdc_checker.py tests/example.c
Processing file tests/example.c
None tree-like decision at:
  tests/example.c line 4, column 12
    Found solution: ['a', 'b', 'c']
```

Using the found solution, we can reorder the condition to `a || b && c`

Our Tool

- We have run our tool on several code bases finding few non-treelike BDDs:
  - On RTEMS SMP
  - On the Mathematical Library for Critical Systems
- This indicates that for many source code pieces gcov is already showing MC/DC.
- The source code changes required to enable gcov to show MC/DC are minimal.
- Other evaluations on industrial code show non-tree like BDDs to be less than 1% of all decisions.

Conclusion

Conclusions on the Method and the Tool

Advantages

- The **method** has been **mathematically proven**.
- Our **tool enables MC/DC** assessment with the **open source** tool **gcov**.
- The required source code changes have very little impact and ensure a good maintainability.
- The structural coverage analysis including MC/DC can be done on target.
- The tool can be freely and easily integrated into existing CI/CD pipelines.

Cautions

- The tool may in some cases not find a solution

  →then manual assessment is still needed.
- The gcov assessment is done on a compilation without optimization (i.e., -O0).
- The gcov assessment requires code instrumentation.
- The tool is not yet qualified.

Thanks

These ideas, methods, and tools heavily base on the work of others.

In particular we want to thank **Andreas Jung** (ESA ESTEC) for stimulating us to find an open source solution for this problem and to **Thanassis Tsiodras** (ESA ESTEC) whose initial works on using gcov for this purpose and discussions led us to these results.