And the truth will make you spin

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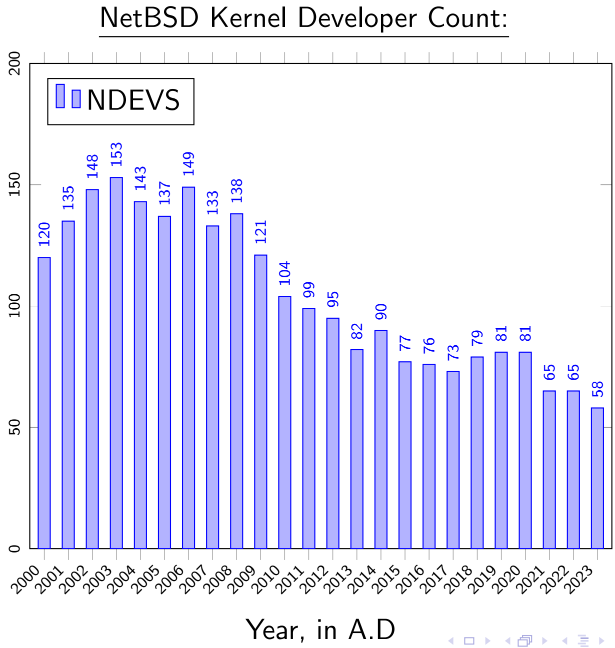
Design Driven Development using the spin verifier.

Audience:

A Software practitioner:

- Dealing with concurrent execution and distributed state. Eg: OS developers.
- Who finds current software system design approaches inadequate.
- For whom descriptive documentation is irksome and inadequate.
- Deal with design issues (for eg: as an "architect")
- Deal with implementation issues (for eg: as an "engineer")

Motivations:



Knowledge Management:

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Knowledge Management:

- Problem:
  - Design crowdsourcing not viable
    - Multiple design opinions about the same code.
    - Documentation/code can drift.
    - Greybeard memory can fade.
    - Unit Testing can only probe points in design space.
- Proposed Solution:
  - Formal Specification
    - Automated verification by model checking.
    - Invariants serve as design **Canon**.

Formal Specification: a trivial example

Consider the following C code:

```
#include <stdio.h>
#include <assert.h>

int j, i, array[10];

void
printarray(void)
{
        for (j = 0; j < 10; j++) {
                i = j;
                printf("array[%d] == %d\n", i, array[i]);
        }
}
```

Formal Specification: a trivial example

Questions such as:

- Why 10 elements, and not 9 or 11 or 1000 ?
- Where is the number of elements specified ?
- What are the edge cases for i and j ?

Formal Specification: a trivial spin example

Specification:

```
#define ARRAYSIZE ARRAYMAX

int j, i, array[ARRAYSIZE];

active proctype printarray()
{
  for (j : 0 .. (ARRAYSIZE - 1)) {
    i = j;
    printf("array[d] == %d\n", i, array[i]);
  }
}
```

Formal Specification: a trivial spin example

Specification State:

```
int j, i, array[ARRAYSIZE];
```

Formal Specification: a trivial spin example

Specification Model:

```
active proctype printarray()
{
  for (j : 0 .. (ARRAYSIZE - 1)) {
    i = j;
    printf("array[d] == %d\n", i, array[i]);
  }
}
```

Formal Specification: a trivial spin example

Specification Invariants:

```
/* Monitors the progress of state variables */
int j, i, array[ARRAYSIZE];
/* Written in "LTL" - Linear Temporal Logic */
ltl  /* Canon */
{
  true
  && (always (ARRAYSIZE == ARRAYMAX))
  && (always ((i >= 0) && i <= (ARRAYMAX - 1)))
  && (eventually always (i == (ARRAYMAX - 1)))
}
```

(D-Cubed) Design Driven Development:

- Inspired from Test Driven Development

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- Inspired from Test Driven Development
- Back to the “Drawing board”
- Paradigm shift from: “start digging” $\Rightarrow$ “start designing”
- ”Drawing board” is formal design
- Verification/consistency of designs can be automated.

(D-Cubed) - process:

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- Extract the model from Implementation (Modex/spin)
- Fidelity checking
- Iterate

(D-Cubed) - case study - Adaptive Replacement Cache

"ARC: A SELF-TUNING, LOW OVERHEAD REPLACEMENT CACHE" by Megiddo et. al.
https://www.usenix.org/legacy/events/fast03/tech/full_papers/megiddo/megiddo.pdf

ARC(c)

INPUT: The request stream $x_1, x_2, \ldots, x_t, \ldots$.
INITIALIZATION: Set $p = 0$ and set the LRU lists T_1, B_1, T_2, and B_2 to empty.

For every $t \geq 1$ and any x_t, one and only one of the following four cases must occur.

Case I: x_t is in T_1 or T_2. A cache hit has occurred in ARC(c) and DBL($2c$).
Move x_t to MRU position in T_2.

Case II: x_t is in B_1. A cache miss (resp. hit) has occurred in ARC(c) (resp. DBL($2c$)).

ADAPTATION: Update $p = \min\{p + \delta_1, c\}$ where $\delta_1 = \begin{cases} 1 & \text{if } |B_1| \geq |B_2| \\ |B_2|/|B_1| & \text{otherwise.} \end{cases}$

REPLACE(x_t, p). Move x_t from B_1 to the MRU position in T_2 (also fetch x_t to the cache).

Case III: x_t is in B_2. A cache miss (resp. hit) has occurred in ARC(c) (resp. DBL($2c$)).

ADAPTATION: Update $p = \max\{p - \delta_2, 0\}$ where $\delta_2 = \begin{cases} 1 & \text{if } |B_2| \geq |B_1| \\ |B_1|/|B_2| & \text{otherwise.} \end{cases}$

REPLACE(x_t, p). Move x_t from B_2 to the MRU position in T_2 (also fetch x_t to the cache).

Case IV: x_t is not in $T_1 \cup B_1 \cup T_2 \cup B_2$. A cache miss has occurred in ARC(c) and DBL($2c$).

```
Case A: L1 = T1 ∪ B1 has exactly c pages.
    If (|T1| < c)
        Delete LRU page in B1. REPLACE(xt, p).
    else
        Here B1 is empty. Delete LRU page in T1 (also remove it from the cache).
    endif
Case B: L1 = T1 ∪ B1 has less than c pages.
    If (|T1| + |T2| + |B1| + |B2| ≥ c)
        Delete LRU page in B2, if (|T1| + |T2| + |B1| + |B2| = 2c).
        REPLACE(xt, p).
    endif
Finally, fetch xt to the cache and move it to MRU position in T1.
```

Subroutine REPLACE(x_t, p)

```
If ( (|T1| is not empty) and ( (|T1| exceeds the target p) or (xt is in B2 and |T1| = p)) )
    Delete the LRU page in T1 (also remove it from the cache), and move it to MRU position in B1.
else
    Delete the LRU page in T2 (also remove it from the cache), and move it to MRU position in B2.
endif
```

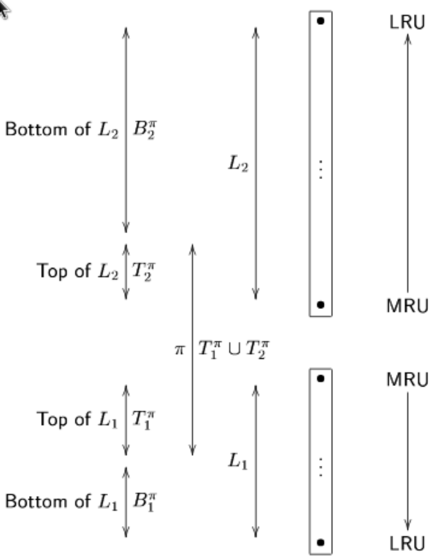
(D-Cubed) - case study - Adaptive Replacement Cache

mail to tech-kern@ and code listing:

https://mail-index.netbsd.org/tech-kern/2023/09/28/msg029203.html

(D-Cubed) - case study - Adaptive Replacement Cache

ARC Caches and state variables.



State Variables

- Buffers T1 U B1 == L1
- Buffers T2 U B2 == L2
- variable p - "Tunable Parameter"
- C - half the size of the Cache

(D-Cubed) - case study - Adaptive Replacement Cache

Specification Invariants:

```
ltl
{
        /* c.f Section I. B, on page 3 of paper */
        always ((lengthof(T1) +
                 lengthof(B1) +
                 lengthof(T2) +
                 lengthof(B2)) <= (2 * C))

        /* Reading together Section III. A., on page
             7, and
         * Section III. B., on pages 7,8
         */
        && always ((lengthof(T1) + lengthof(B1)) <=
             C)
        && always ((lengthof(T2) + lengthof(B2)) <=
             (2 * C))

        /* Section III. B, Remark III.1 */
        && always ((lengthof(T1) + lengthof(T2)) <=
             C)

        /* TODO: III B, A.1 */

        /* III B, A.2 */
        && always (((lengthof(T1) +
                  lengthof(B1) +
                  lengthof(T2) +
                  lengthof(B2)) < C)
                 implies ((lengthof(B1) == 0) &&
                      lengthof(B2) == 0))

        /* III B, A.3 */
        && always (((lengthof(T1) +
                  lengthof(B1) +
                  lengthof(T2) +
                  lengthof(B2)) >= C)
                 implies ((lengthof(T1) +
                      lengthof(T2)) == C))

        /* TODO: III B, A.4 */

        /* TODO: III B, A.5 */

        /* IV A. */
        && always (p <= C)

        /*
         * Force spin to generate a "good" input
              trace (See: arc.drv)
         * The handwavy reasoning here is that an
              absolutely full ARC
         * would have had to exercise all codepaths
              to get there.
         */
        && always !(true /* Syntactic glue */
                 && lengthof(T1) == C
                 && lengthof(B1) == C
                 && lengthof(T2) == C
                 && lengthof(B2) == C
                 )
}
```

(D-Cubed) - case study - Adaptive Replacement Cache

Specification Invariants:

On LTL:

- assert() checks for current status of variable ***NOW***.
- LTL checks along the entire life of the state machine.

(D-Cubed) - case study - Adaptive Replacement Cache

Specification Invariants:

"Propositional Logic".
for example:

```
int x;

...

void
test(void)
{
    assert(x == SOMEVALUE);
}

/*
 * Implies x should be that value at that
 * specific execution point.
 */
```

(D-Cubed) - case study - Adaptive Replacement Cache

Specification Invariants:

LTL - or Linear Temporal Logic
for example:

```
int x;

...

ltl
{
    always (x == SOMEVALUE)
}

/*
 * Implies x should be that value throughout
 * execution.
 */
```

(D-Cubed) - Model Extraction

The spin companion "Model Extractor"(modex) can extract a model implicit within C code. This extraction is guided by a bespoke language "prx" which modex uses.

for example:

```
%F test.c
%X -n test

/*
 * Extract model from test.c:test()
 */
```

Fidelity Checking:

Does:

```
ltl
{
    always (x == SOMEVALUE)
}
```

Still pass ?

(D-Cubed) - Model Extraction

Model Extraction:

Extraction gives us a spin model file with the following content:

```
// Generated by MODEX Version 2.11 - 3 November 2017
// Sat 23 Mar 2024 10:38:18 PM IST from test.prx

int x;
proctype p_test( )
{
      c_code [(now.x==SOMEVALUE)] { ; };
}
```

We can now use a common driver to drive this “Hub” being checked.

```
init {
    pid n;
    n = run p_test();

    (n == _nr_pr); /* Wait for p_test() to exit */
}
```

(D-Cubed) - Model Driver

Spin as implementation driver:

- modex parser is flaky
- hook up spin to drive test() directly.

```
int x;
proctype p_test( )
{
    c_code {
    int x;
    x = now.x;
    test();
    }
}

...

$ spin -D SOMEVALUE=1 -a test.drv
$ cc -D SOMEVALUE=1 -o test pan.c test.c
$ ./test
```

(D-Cubed) - case study - Adaptive Replacement Cache

Specification Invariants:

Pros	**Cons**
- Explicit design visibility	- Dev time can be ~2.5x
- Debugging reduced by ~90%	- Model/Implementation sync overhead
- Can ask new falsifiable questions via LTL	- Poorly crafted LTL can blur design clarity
- Can integrate into CI	- poorly crafted constraints can stall CI

(D-Cubed) - differences with MBSE/Systems Modelling:

- Requirements are at the State Machine level
- No code generation
- Fidelity checking
- Integrated with CI

(D-Cubed) - TODO for Spin/Modex on NetBSD

- Modex is flaky - re-write parser for C99
- Harness needs (language) re-design

(D-Cubed) - first steps for NetBSD. (WIP)

- Alternative method, without Modex (because of broken C-lang parser).
- Existing NetBSD code:
  - spin as "driver" for "Rump"-ed C code.
  - standalone verification possible.
  - glue code instead of modex.
- Pro: Existing code can be dropin verified.
- Con: Extracted model replaced by glue code updating model state on behalf of C code. Verification blindspot.

(D-Cubed) - introducing “SpinOS”

- Capture design models of various “Hub”s in NetBSD
- Record Invariants as design documentation
- Comprehensive formal design of a real world OS
- Fidelity checking to keep model “grounded”
- Can be used as basis for D-Cubed based development in several OSs.
- Please join the project! (Send me email, for now).

(D-Cubed) Roadmap:

- Develop SpinOS as canonical model for NetBSD.
- Integrate SpinOS elements into NetBSD CI
- Auto-generate documentation (man pages for eg:) from LTL.
- RAG - Online Oracle for greybeard style Q&A

(D-Cubed) Questions ?:

Fediverse:

`@c@bow.st`

$\Leftarrow$

Scan QR Code for consulting.