# マイクロアーキテクチャ攻撃演習２

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## 演習の概要

- Spectre を実際にプロセッサシミュレータで実行
- プロセッサ内で命令が実行される様子を実際に見て、攻撃の仕組みをより深く理解する

## 今回の内容

- 今回は実践編
  - プロセッサシミュレータでspectreを動かし、その実行の様子をパイプラインビューアで確認する
  - spectre の脆弱性の回避方法を実践する

- 主な内容
  1. gem5でspectreを実行
  2. 実行履歴をパイプラインビューアで表示
  3. 攻撃箇所を特定し、プログラムと照らし合わせる
  4. spectre のプログラムを一部変更して脆弱性を回避する

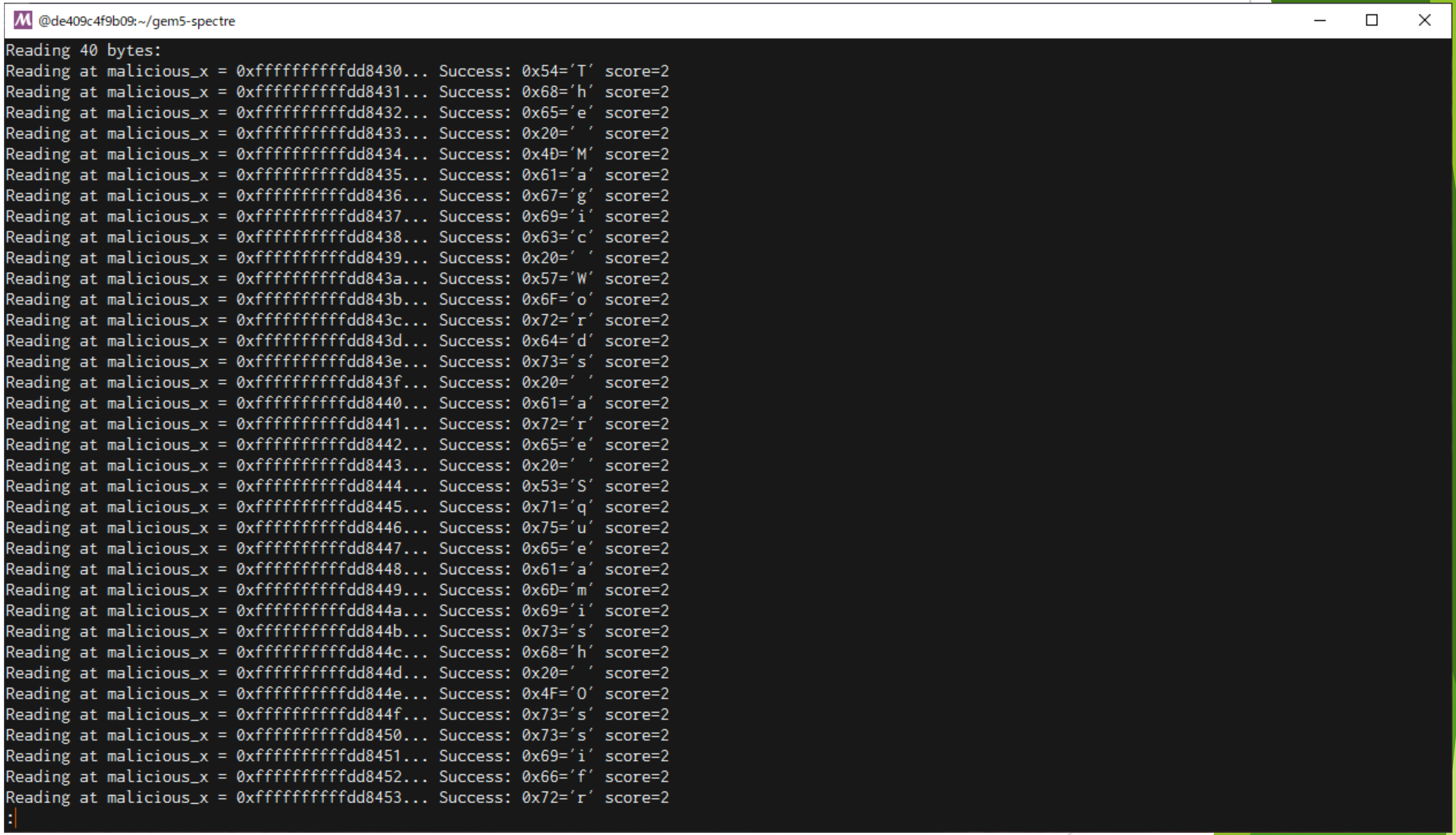
# Spectre proof of concept

- https://gist.github.com/ErikAugust/724d4a969fb2c6ae1bbd7b2a9e3d4bb6
  - 一部修正が必要（Dockerでは適用済み）
  - /home/gem5user/gem5-spectre/spectre に配置済み
- そのまま実行してみましょう

```
$ cd /home/gem5user/gem5-spectre
$ spectre/spectre | less
```

- １プロセス内で直接データにアクセスせずに値を推測できることを実証するプログラム

## Spectre 実行結果

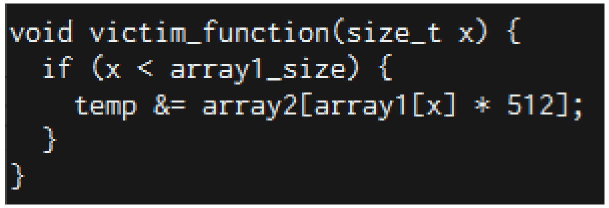


```
Reading 40 bytes:
Reading at malicious_x = 0xffffffffffdd8430... Success: 0x54='T' score=2
Reading at malicious_x = 0xffffffffffdd8431... Success: 0x68='h' score=2
Reading at malicious_x = 0xffffffffffdd8432... Success: 0x65='e' score=2
Reading at malicious_x = 0xffffffffffdd8433... Success: 0x20=' ' score=2
Reading at malicious_x = 0xffffffffffdd8434... Success: 0x4D='M' score=2
Reading at malicious_x = 0xffffffffffdd8435... Success: 0x61='a' score=2
Reading at malicious_x = 0xffffffffffdd8436... Success: 0x67='g' score=2
Reading at malicious_x = 0xffffffffffdd8437... Success: 0x69='i' score=2
Reading at malicious_x = 0xffffffffffdd8438... Success: 0x63='c' score=2
Reading at malicious_x = 0xffffffffffdd8439... Success: 0x20=' ' score=2
Reading at malicious_x = 0xffffffffffdd843a... Success: 0x57='W' score=2
Reading at malicious_x = 0xffffffffffdd843b... Success: 0x6F='o' score=2
Reading at malicious_x = 0xffffffffffdd843c... Success: 0x72='r' score=2
Reading at malicious_x = 0xffffffffffdd843d... Success: 0x64='d' score=2
Reading at malicious_x = 0xffffffffffdd843e... Success: 0x73='s' score=2
Reading at malicious_x = 0xffffffffffdd843f... Success: 0x20=' ' score=2
Reading at malicious_x = 0xffffffffffdd8440... Success: 0x61='a' score=2
Reading at malicious_x = 0xffffffffffdd8441... Success: 0x72='r' score=2
Reading at malicious_x = 0xffffffffffdd8442... Success: 0x65='e' score=2
Reading at malicious_x = 0xffffffffffdd8443... Success: 0x20=' ' score=2
Reading at malicious_x = 0xffffffffffdd8444... Success: 0x53='S' score=2
Reading at malicious_x = 0xffffffffffdd8445... Success: 0x71='q' score=2
Reading at malicious_x = 0xffffffffffdd8446... Success: 0x75='u' score=2
Reading at malicious_x = 0xffffffffffdd8447... Success: 0x65='e' score=2
Reading at malicious_x = 0xffffffffffdd8448... Success: 0x61='a' score=2
Reading at malicious_x = 0xffffffffffdd8449... Success: 0x6D='m' score=2
Reading at malicious_x = 0xffffffffffdd844a... Success: 0x69='i' score=2
Reading at malicious_x = 0xffffffffffdd844b... Success: 0x73='s' score=2
Reading at malicious_x = 0xffffffffffdd844c... Success: 0x68='h' score=2
Reading at malicious_x = 0xffffffffffdd844d... Success: 0x20=' ' score=2
Reading at malicious_x = 0xffffffffffdd844e... Success: 0x4F='O' score=2
Reading at malicious_x = 0xffffffffffdd844f... Success: 0x73='s' score=2
Reading at malicious_x = 0xffffffffffdd8450... Success: 0x73='s' score=2
Reading at malicious_x = 0xffffffffffdd8451... Success: 0x69='i' score=2
Reading at malicious_x = 0xffffffffffdd8452... Success: 0x66='f' score=2
Reading at malicious_x = 0xffffffffffdd8453... Success: 0x72='r' score=2
:
```

# Spectre の解析

- Objdumpしてみましょう

```
$ cd /home/gem5user/gem5-spectre
$ objdump -D spectre/spectre | less
```



```
void victim_function(size_t x) {
  if (x < array1_size) {
    temp &= array2[array1[x] * 512];
  }
}
```

投機実行させたい処理
spectre/spectre.c

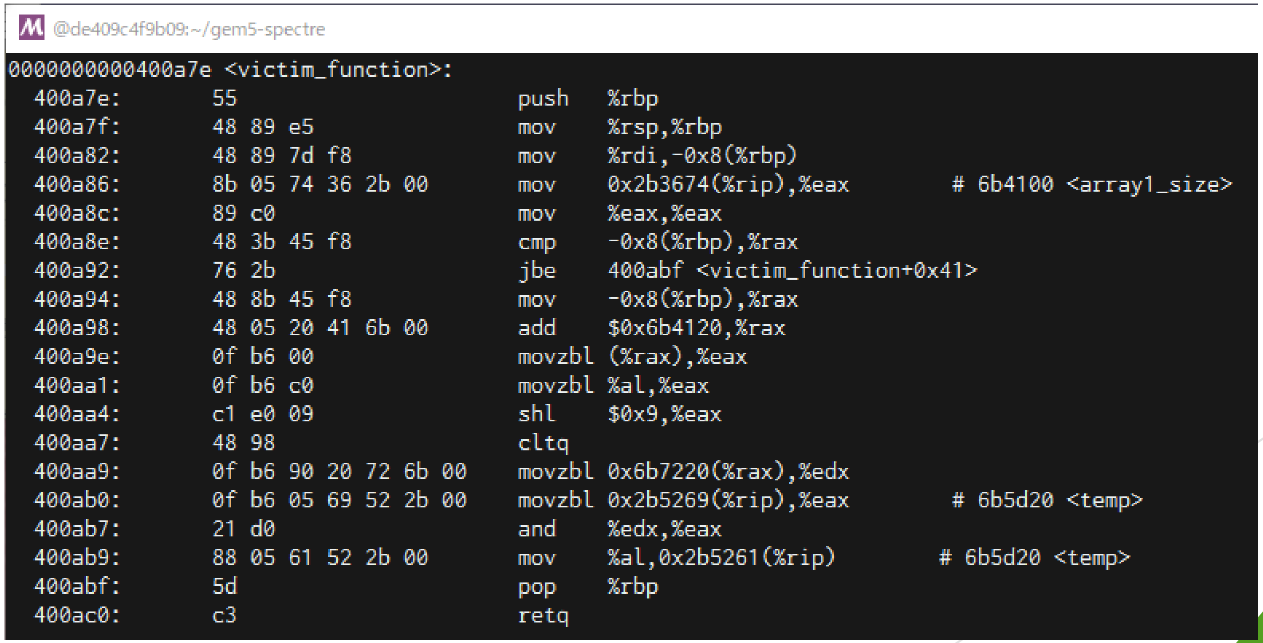
# Spectre の解析

- Objdumpしてみましょう

```
$ cd /home/gem5user/gem5-spectre
$ objdump -D spectre/spectre | less
```

```
void victim_function(size_t x) {
  if (x < array1_size) {
    temp &= array2[array1[x] * 512];
  }
}
```

該当する命令列
投機実行させたい命令はどれ？



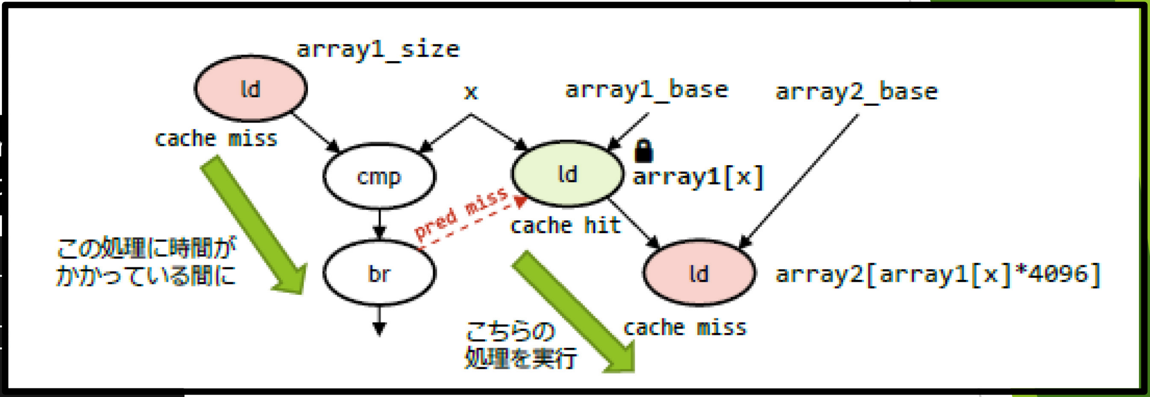
```
@de409c4f9b09:~/gem5-spectre
0000000000400a7e <victim_function>:
  400a7e:       55                      push   %rbp
  400a7f:       48 89 e5                mov    %rsp,%rbp
  400a82:       48 89 7d f8             mov    %rdi,-0x8(%rbp)
  400a86:       8b 05 74 36 2b 00       mov    0x2b3674(%rip),%eax        # 6b4100 <array1_size>
  400a8c:       89 c0                   mov    %eax,%eax
  400a8e:       48 3b 45 f8             cmp    -0x8(%rbp),%rax
  400a92:       76 2b                   jbe    400abf <victim_function+0x41>
  400a94:       48 8b 45 f8             mov    -0x8(%rbp),%rax
  400a98:       48 05 20 41 6b 00       add    $0x6b4120,%rax
  400a9e:       0f b6 00                movzbl (%rax),%eax
  400aa1:       0f b6 c0                movzbl %al,%eax
  400aa4:       c1 e0 09                shl    $0x9,%eax
  400aa7:       48 98                   cltq
  400aa9:       0f b6 90 20 72 6b 00    movzbl 0x6b7220(%rax),%edx
  400ab0:       0f b6 05 69 52 2b 00    movzbl 0x2b5269(%rip),%eax        # 6b5d20 <temp>
  400ab7:       21 d0                   and    %edx,%eax
  400ab9:       88 05 61 52 2b 00       mov    %al,0x2b5261(%rip)        # 6b5d20 <temp>
  400abf:       5d                      pop    %rbp
  400ac0:       c3                      retq
```

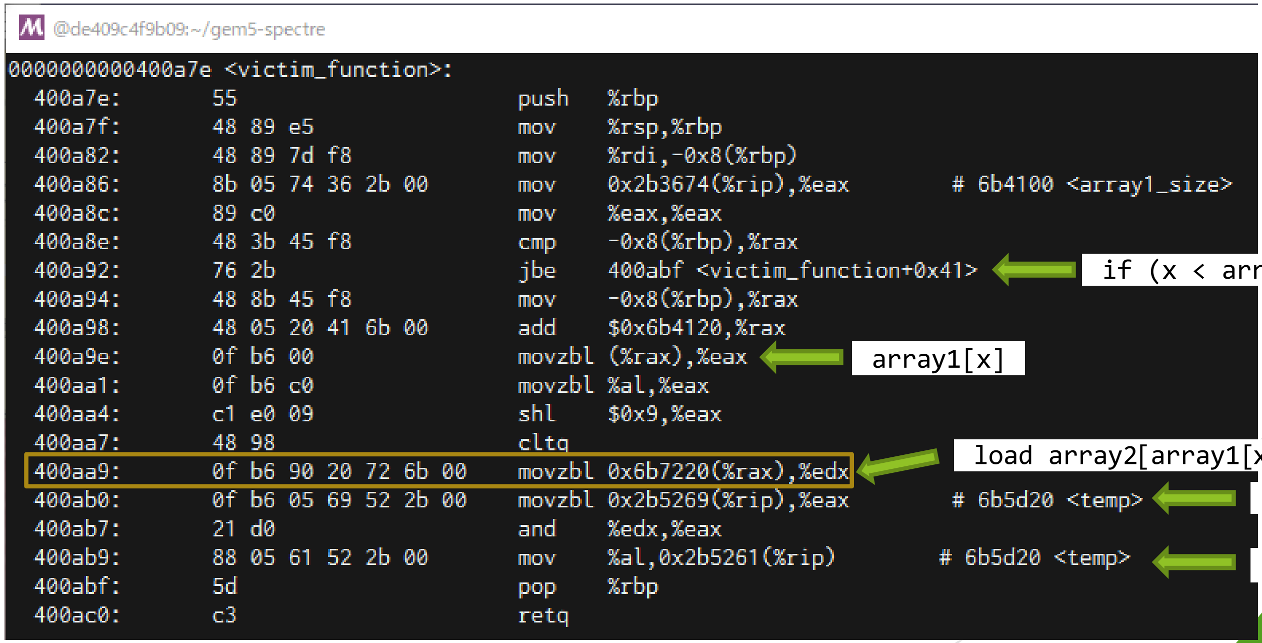
# Spectre の解析

- Objdumpしてみま

```
$ cd /home/gem5user/gem
$ objdump -D spectre/sp
```

```
void victim_function(size_
  if (x < array1_size) {
    temp &= array2[array1[
  }
}
```





```
0000000000400a7e <victim_function>:
  400a7e:       55                      push   %rbp
  400a7f:       48 89 e5                mov    %rsp,%rbp
  400a82:       48 89 7d f8             mov    %rdi,-0x8(%rbp)
  400a86:       8b 05 74 36 2b 00       mov    0x2b3674(%rip),%eax        # 6b4100 <array1_size>
  400a8c:       89 c0                   mov    %eax,%eax
  400a8e:       48 3b 45 f8             cmp    -0x8(%rbp),%rax
  400a92:       76 2b                   jbe    400abf <victim_function+0x41>
  400a94:       48 8b 45 f8             mov    -0x8(%rbp),%rax
  400a98:       48 05 20 41 6b 00       add    $0x6b4120,%rax
  400a9e:       0f b6 00                movzbl (%rax),%eax
  400aa1:       0f b6 c0                movzbl %al,%eax
  400aa4:       c1 e0 09                shl    $0x9,%eax
  400aa7:       48 98                   cltq
  400aa9:       0f b6 90 20 72 6b 00    movzbl 0x6b7220(%rax),%edx
  400ab0:       0f b6 05 69 52 2b 00    movzbl 0x2b5269(%rip),%eax        # 6b5d20 <temp>
  400ab7:       21 d0                   and    %edx,%eax
  400ab9:       88 05 61 52 2b 00       mov    %al,0x2b5261(%rip)        # 6b5d20 <temp>
  400abf:       5d                      pop    %rbp
  400ac0:       c3                      retq
```

```
if (x < array1_size)
array1[x]
load array2[array1[x] * 512]
load temp
store temp
```

# gem5でspectreを実行する

- 以下のようにして実行してみましょう

```
$ cd /home/gem5user/gem5-spectre
$ gem5/build/X86/gem5.opt ¥
    --debug-flags=O3PipeView ¥
    --debug-file=pipeview.txt ¥
    --debug-start=1306234700 ¥
    –d gem5out/spectre ¥
    gem5/configs/learning_gem5/part1/two_level_o3ltage.py ¥
    spectre/spectre
```

  - ¥ はバックスラッシュに読み替えてください
  - --debug-flags：シミュレータのデバッグフラグを有効に
  - --debug-file：デバッグ情報の出力先指定
  - --debug-start：指定した時刻からデバッグ出力を開始
- Success: を含む行が２～３行出力されたらControl-Cでシミュレータを停止

# 出力ファイルの変換

- 以下のコマンドで出力ファイルを変換

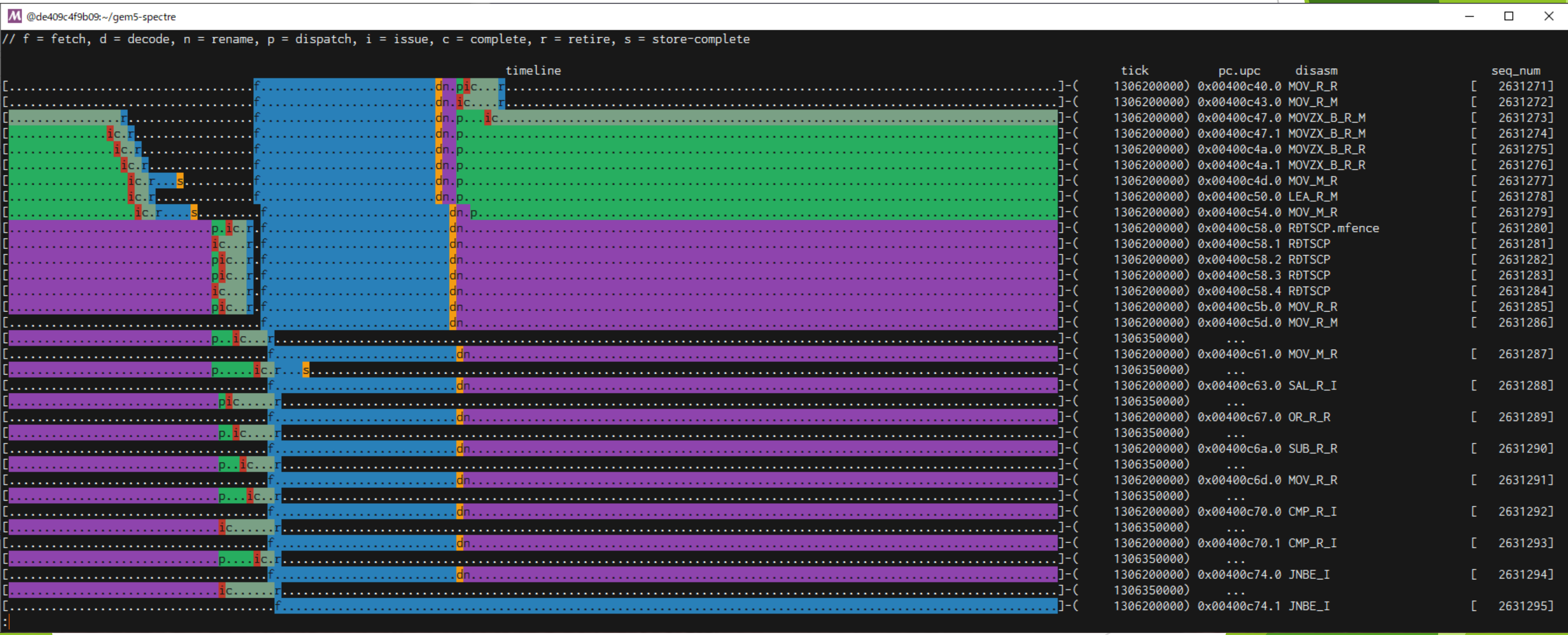
```
$ gem5/util/o3-pipeview.py --store_completions ¥
   gem5out/spectre/pipeview.txt --color -w 150
```

  - -w 150 はターミナルの幅なので、お使いのターミナルの幅に合わせて変更してください
  - o3-pipeview.out が出力されます

# パイプラインの確認

- 以下のコマンドでパイプラインを表示

```
$ less -r o3-pipeview.out
```

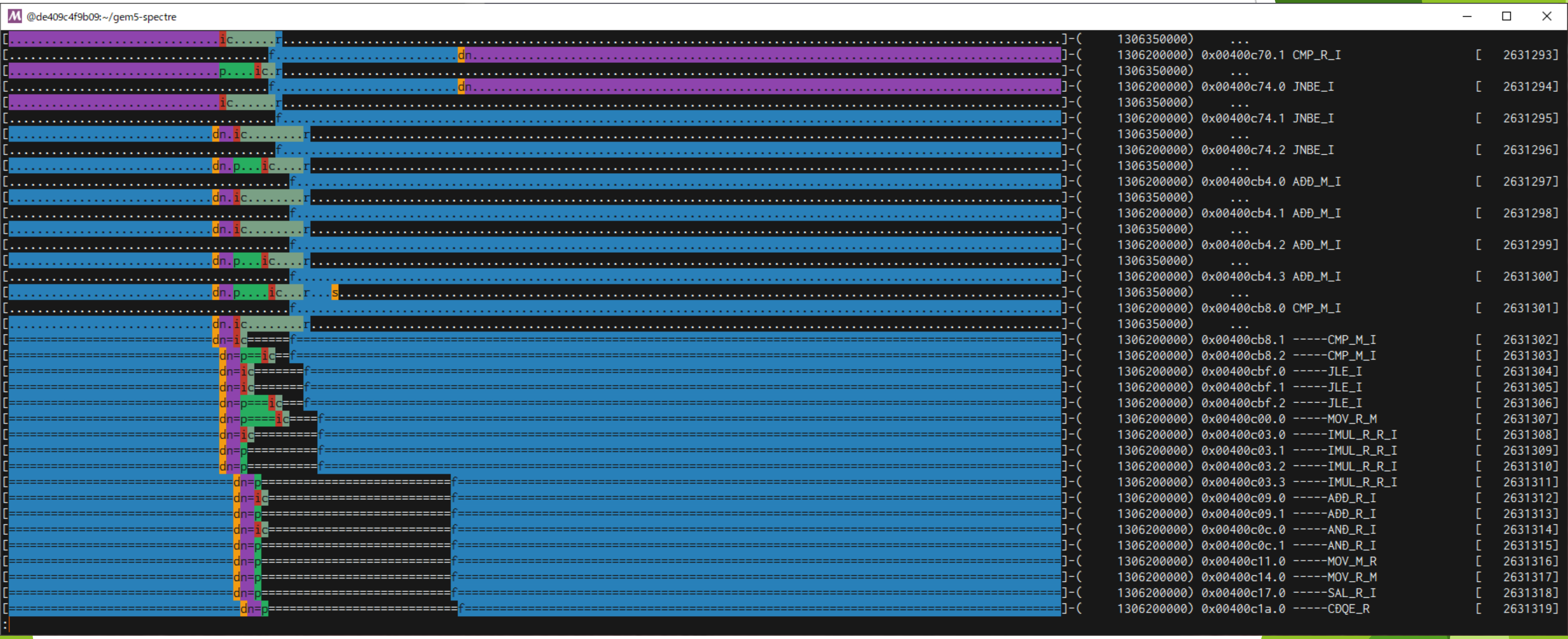


@de409c4f9b09:~/gem5-spectre

```
// f = fetch, d = decode, n = rename, p = dispatch, i = issue, c = complete, r = retire, s = store-complete

                                                                        timeline                                                                               tick          pc.upc     disasm                      seq_num
[...................................f.........................dn.pic...r..............................................................................]-(     1306200000) 0x00400c40.0 MOV_R_R                   [   2631271]
[...................................f.........................dn.ic....r..............................................................................]-(     1306200000) 0x00400c43.0 MOV_R_M                   [   2631272]
[................r..................f.........................dn.p...ic...............................................................................]-(     1306200000) 0x00400c47.0 MOVZX_B_R_M               [   2631273]
[..............ic.r.................f.........................dn.p....................................................................................]-(     1306200000) 0x00400c47.1 MOVZX_B_R_M               [   2631274]
[...............ic.r................f.........................dn.p....................................................................................]-(     1306200000) 0x00400c4a.0 MOVZX_B_R_R               [   2631275]
[................ic.r...............f.........................dn.p....................................................................................]-(     1306200000) 0x00400c4a.1 MOVZX_B_R_R               [   2631276]
[.................ic.r...s..........f.........................dn.p....................................................................................]-(     1306200000) 0x00400c4d.0 MOV_M_R                   [   2631277]
[.................ic.r..............f.........................dn.p....................................................................................]-(     1306200000) 0x00400c50.0 LEA_R_M                   [   2631278]
[..................ic.r....s.........f..........................dn.p..................................................................................]-(     1306200000) 0x00400c54.0 MOV_M_R                   [   2631279]
[.............................p.ic.r.f..........................dn....................................................................................]-(     1306200000) 0x00400c58.0 RDTSCP.mfence             [   2631280]
[.............................ic...r.f..........................dn....................................................................................]-(     1306200000) 0x00400c58.1 RDTSCP                    [   2631281]
[.............................pic..r.f..........................dn....................................................................................]-(     1306200000) 0x00400c58.2 RDTSCP                    [   2631282]
[.............................pic..r.f..........................dn....................................................................................]-(     1306200000) 0x00400c58.3 RDTSCP                    [   2631283]
[.............................ic...r.f..........................dn....................................................................................]-(     1306200000) 0x00400c58.4 RDTSCP                    [   2631284]
[.............................pic..r.f..........................dn....................................................................................]-(     1306200000) 0x00400c5b.0 MOV_R_R                   [   2631285]
[....................................f..........................dn....................................................................................]-(     1306200000) 0x00400c5d.0 MOV_R_M                   [   2631286]
[.............................p..ic...r...............................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn...................................................................................]-(     1306200000) 0x00400c61.0 MOV_M_R                   [   2631287]
[.............................p.....ic.r...s..........................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn...................................................................................]-(     1306200000) 0x00400c63.0 SAL_R_I                   [   2631288]
[..............................pic.....r..............................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn...................................................................................]-(     1306200000) 0x00400c67.0 OR_R_R                    [   2631289]
[..............................p.ic....r..............................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn...................................................................................]-(     1306200000) 0x00400c6a.0 SUB_R_R                   [   2631290]
[..............................p..ic...r..............................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn...................................................................................]-(     1306200000) 0x00400c6d.0 MOV_R_R                   [   2631291]
[..............................p...ic..r..............................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn...................................................................................]-(     1306200000) 0x00400c70.0 CMP_R_I                   [   2631292]
[..............................ic......r..............................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn...................................................................................]-(     1306200000) 0x00400c70.1 CMP_R_I                   [   2631293]
[..............................p....ic.r..............................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn...................................................................................]-(     1306200000) 0x00400c74.0 JNBE_I                    [   2631294]
[..............................ic......r..............................................................................................................]-(     1306350000)     ...
[......................................f..............................................................................................................]-(     1306200000) 0x00400c74.1 JNBE_I                    [   2631295]
:
```

# 投機ミスした処理

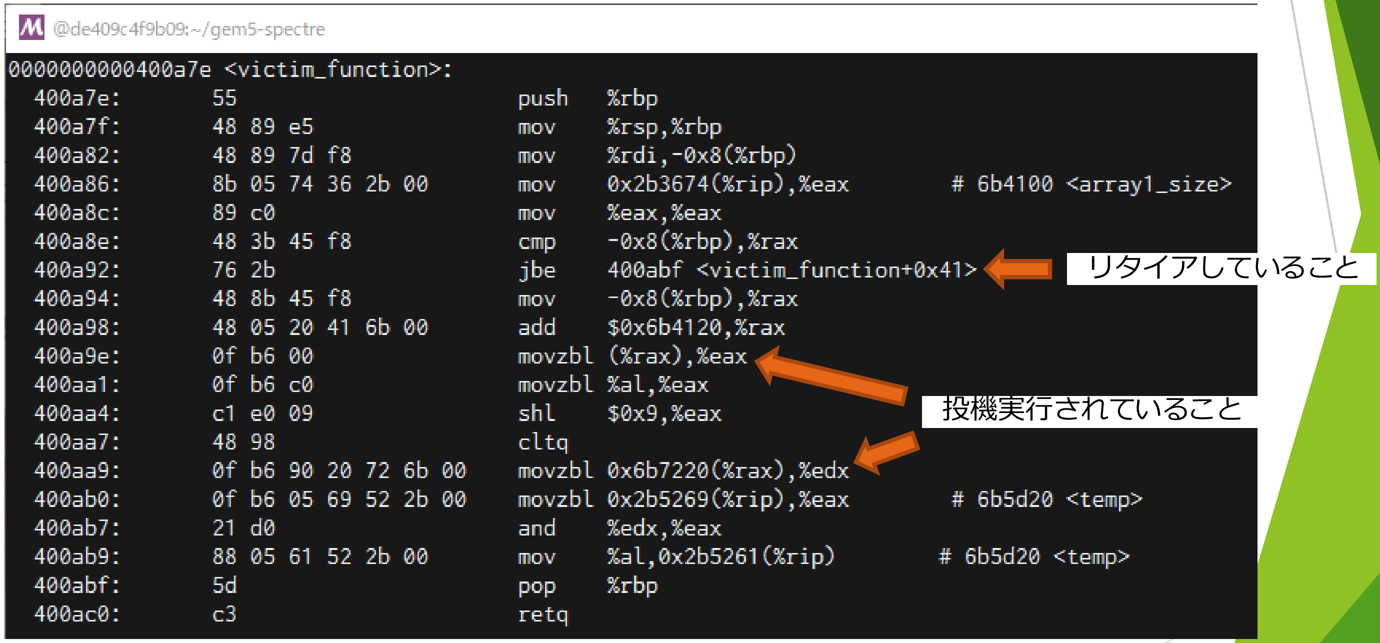


@de409c4f9b09:~/gem5-spectre

```
[..............................ic......r...............................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn....................................................................................]-(     1306200000) 0x00400c70.1 CMP_R_I                   [   2631293]
[..............................p....ic.r...............................................................................................................]-(     1306350000)     ...
[.....................................f..........................dn....................................................................................]-(     1306200000) 0x00400c74.0 JNBE_I                    [   2631294]
[..............................ic......r...............................................................................................................]-(     1306350000)     ...
[......................................f...............................................................................................................]-(     1306200000) 0x00400c74.1 JNBE_I                    [   2631295]
[.............................dn.ic........r...........................................................................................................]-(     1306350000)     ...
[......................................f...............................................................................................................]-(     1306200000) 0x00400c74.2 JNBE_I                    [   2631296]
[.............................dn.p...ic....r...........................................................................................................]-(     1306350000)     ...
[........................................f.............................................................................................................]-(     1306200000) 0x00400cb4.0 ADD_M_I                   [   2631297]
[.............................dn.ic........r...........................................................................................................]-(     1306350000)     ...
[........................................f.............................................................................................................]-(     1306200000) 0x00400cb4.1 ADD_M_I                   [   2631298]
[.............................dn.ic........r...........................................................................................................]-(     1306350000)     ...
[........................................f.............................................................................................................]-(     1306200000) 0x00400cb4.2 ADD_M_I                   [   2631299]
[.............................dn.p...ic....r...........................................................................................................]-(     1306350000)     ...
[........................................f.............................................................................................................]-(     1306200000) 0x00400cb4.3 ADD_M_I                   [   2631300]
[.............................dn.p....ic...r...s.......................................................................................................]-(     1306350000)     ...
[........................................f.............................................................................................................]-(     1306200000) 0x00400cb8.0 CMP_M_I                   [   2631301]
[.............................dn.ic........r...........................................................................................................]-(     1306350000)     ...
[=============================dn=ic======f=============================================================================================================]-(     1306200000) 0x00400cb8.1 -----CMP_M_I              [   2631302]
[==============================dn=p==ic==f=============================================================================================================]-(     1306200000) 0x00400cb8.2 -----CMP_M_I              [   2631303]
[==============================dn=ic=======f===========================================================================================================]-(     1306200000) 0x00400cbf.0 -----JLE_I                [   2631304]
[==============================dn=ic=======f===========================================================================================================]-(     1306200000) 0x00400cbf.1 -----JLE_I                [   2631305]
[==============================dn=p===ic===f===========================================================================================================]-(     1306200000) 0x00400cbf.2 -----JLE_I                [   2631306]
[==============================dn=p====ic====f=========================================================================================================]-(     1306200000) 0x00400c00.0 -----MOV_R_M              [   2631307]
[==============================dn=ic=========f=========================================================================================================]-(     1306200000) 0x00400c03.0 -----IMUL_R_R_I           [   2631308]
[==============================dn=p==========f=========================================================================================================]-(     1306200000) 0x00400c03.1 -----IMUL_R_R_I           [   2631309]
[==============================dn=p==========f=========================================================================================================]-(     1306200000) 0x00400c03.2 -----IMUL_R_R_I           [   2631310]
[================================dn=p===========================f======================================================================================]-(     1306200000) 0x00400c03.3 -----IMUL_R_R_I           [   2631311]
[================================dn=ic==========================f======================================================================================]-(     1306200000) 0x00400c09.0 -----ADD_R_I              [   2631312]
[================================dn=p===========================f======================================================================================]-(     1306200000) 0x00400c09.1 -----ADD_R_I              [   2631313]
[================================dn=ic==========================f======================================================================================]-(     1306200000) 0x00400c0c.0 -----AND_R_I              [   2631314]
[================================dn=p===========================f======================================================================================]-(     1306200000) 0x00400c0c.1 -----AND_R_I              [   2631315]
[================================dn=p===========================f======================================================================================]-(     1306200000) 0x00400c11.0 -----MOV_M_R              [   2631316]
[================================dn=p===========================f======================================================================================]-(     1306200000) 0x00400c14.0 -----MOV_R_M              [   2631317]
[================================dn=p===========================f======================================================================================]-(     1306200000) 0x00400c17.0 -----SAL_R_I              [   2631318]
[=================================dn=p===========================f=====================================================================================]-(     1306200000) 0x00400c1a.0 -----CDQE_R               [   2631319]
:
```

## Spectreが起きている箇所

- パイプラインを調べてSpectreの攻撃が起きている箇所を特定しましょう
  - ヒント

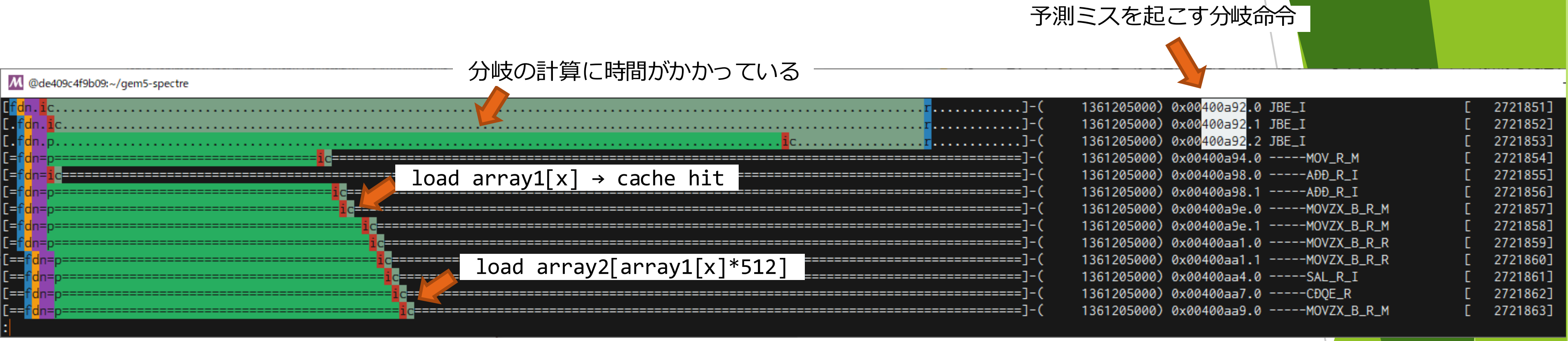


@de409c4f9b09:~/gem5-spectre

```
0000000000400a7e <victim_function>:
  400a7e:       55                      push   %rbp
  400a7f:       48 89 e5                mov    %rsp,%rbp
  400a82:       48 89 7d f8             mov    %rdi,-0x8(%rbp)
  400a86:       8b 05 74 36 2b 00       mov    0x2b3674(%rip),%eax        # 6b4100 <array1_size>
  400a8c:       89 c0                   mov    %eax,%eax
  400a8e:       48 3b 45 f8             cmp    -0x8(%rbp),%rax
  400a92:       76 2b                   jbe    400abf <victim_function+0x41>
  400a94:       48 8b 45 f8             mov    -0x8(%rbp),%rax
  400a98:       48 05 20 41 6b 00       add    $0x6b4120,%rax
  400a9e:       0f b6 00                movzbl (%rax),%eax
  400aa1:       0f b6 c0                movzbl %al,%eax
  400aa4:       c1 e0 09                shl    $0x9,%eax
  400aa7:       48 98                   cltq
  400aa9:       0f b6 90 20 72 6b 00    movzbl 0x6b7220(%rax),%edx
  400ab0:       0f b6 05 69 52 2b 00    movzbl 0x2b5269(%rip),%eax        # 6b5d20 <temp>
  400ab7:       21 d0                   and    %edx,%eax
  400ab9:       88 05 61 52 2b 00       mov    %al,0x2b5261(%rip)        # 6b5d20 <temp>
  400abf:       5d                      pop    %rbp
  400ac0:       c3                      retq
```

# Spectreが起きている箇所

- 見つかりましたか？


予測ミスを起こす分岐命令
分岐の計算に時間がかかっている
load array1[x] → cache hit
load array2[array1[x]*512]
@de409c4f9b09:~/gem5-spectre

```
[fdn.ic.......................................................................................................................r............]-(     1361205000) 0x00400a92.0 JBE_I                      [    2721851]
[.fdn.ic......................................................................................................................r............]-(     1361205000) 0x00400a92.1 JBE_I                      [    2721852]
[.fdn.p..................................................................................................ic.................r............]-(     1361205000) 0x00400a92.2 JBE_I                      [    2721853]
[=fdn=p===================================ic=============================================================================================]-(     1361205000) 0x00400a94.0 -----MOV_R_M               [    2721854]
[=fdn=ic=================================================================================================================================]-(     1361205000) 0x00400a98.0 -----ADD_R_I               [    2721855]
[=fdn=p=====================================ic===========================================================================================]-(     1361205000) 0x00400a98.1 -----ADD_R_I               [    2721856]
[=fdn=p======================================ic==========================================================================================]-(     1361205000) 0x00400a9e.0 -----MOVZX_B_R_M           [    2721857]
[=fdn=p=========================================ic=======================================================================================]-(     1361205000) 0x00400a9e.1 -----MOVZX_B_R_M           [    2721858]
[=fdn=p==========================================ic======================================================================================]-(     1361205000) 0x00400aa1.0 -----MOVZX_B_R_R           [    2721859]
[==fdn=p==========================================ic=====================================================================================]-(     1361205000) 0x00400aa1.1 -----MOVZX_B_R_R           [    2721860]
[==fdn=p===========================================ic====================================================================================]-(     1361205000) 0x00400aa4.0 -----SAL_R_I               [    2721861]
[==fdn=p============================================ic===================================================================================]-(     1361205000) 0x00400aa7.0 -----CDQE_R                [    2721862]
[==fdn=p=============================================ic==================================================================================]-(     1361205000) 0x00400aa9.0 -----MOVZX_B_R_M           [    2721863]
:
```

- 分岐結果が決まるまでの間にload命令が投機実行されてデータがキャッシュに乗る

## Spectre 脆弱性の回避

- 資料 1 p.59を参考に spectre を回避しましょう
- 回避できたら、その実行の様子をパイプラインビューアで確認してください
- 対策前と比較して、性能にどのような影響があるか考察してください