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

- 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

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

```
@de409c4f9b09:~/gem5-spectre
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

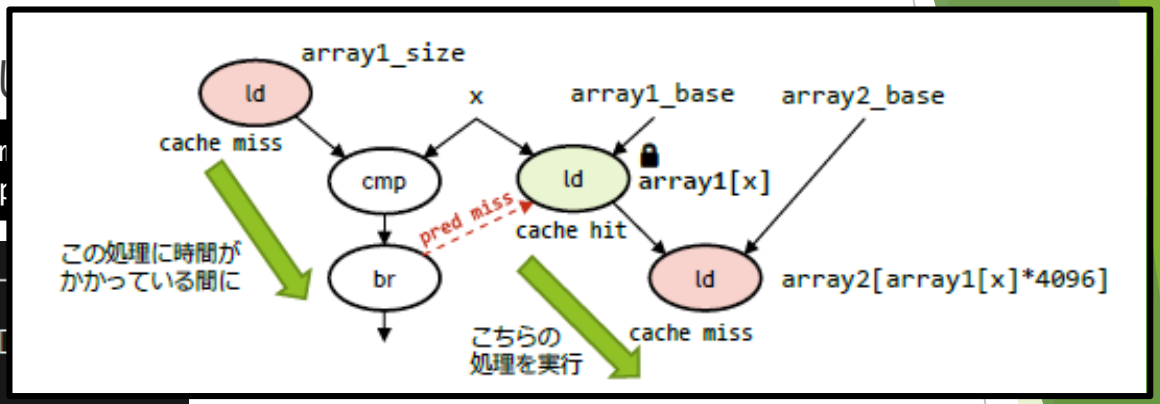
```
0000000000400a7e <victim_function>:
  400a7e:       55                      push   %rbp
  400a7f:       48 89 e5                mov    %rsp,%rbp
  400a82:       48 89 7d f8             mov    %rdi,-0x8(%rbp)
  400a86:       8b 05 74 36 2b 00       mov    0x2b3674(%rip),%eax        # 6b4100 <array1_size>
  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してみまし

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

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



@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
```

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

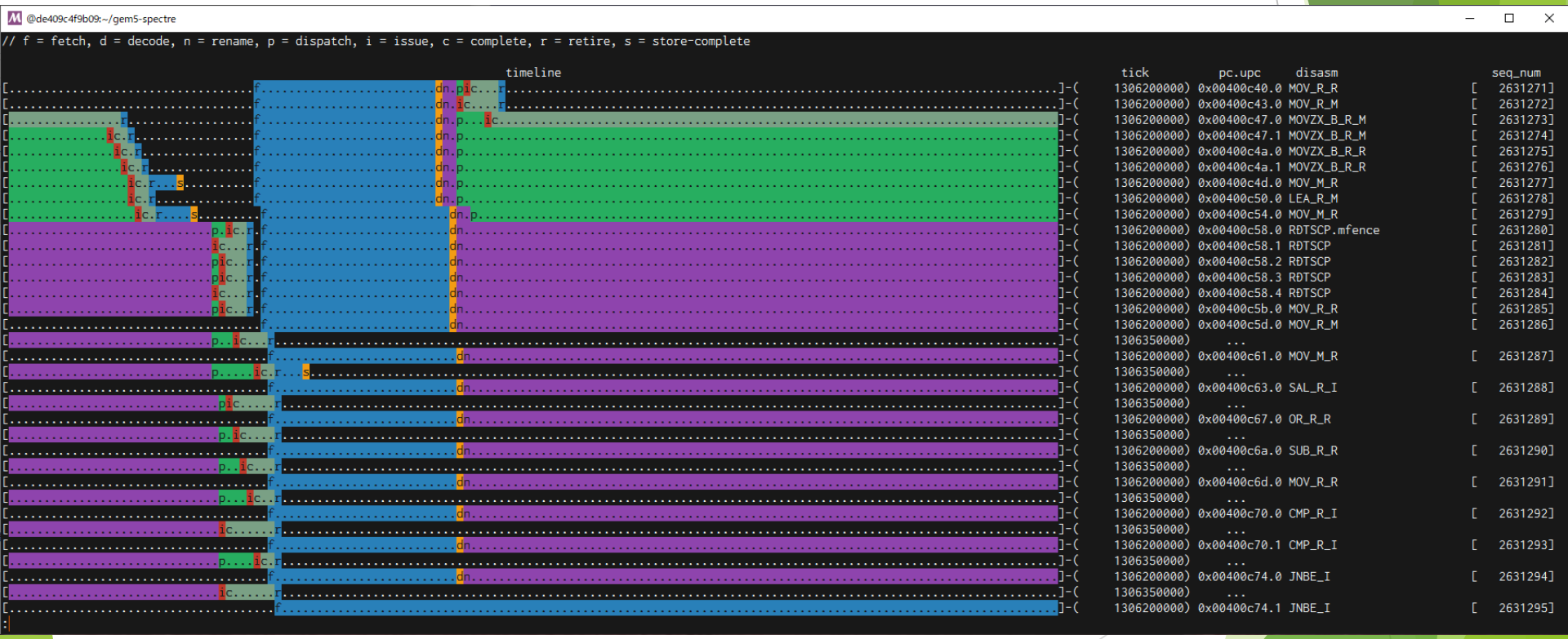
```
$ gem5/util/o3-pipeview.py --store_completions ¥
  gem5out/spectre/pipeview.txt --color -w 150
```

  - -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

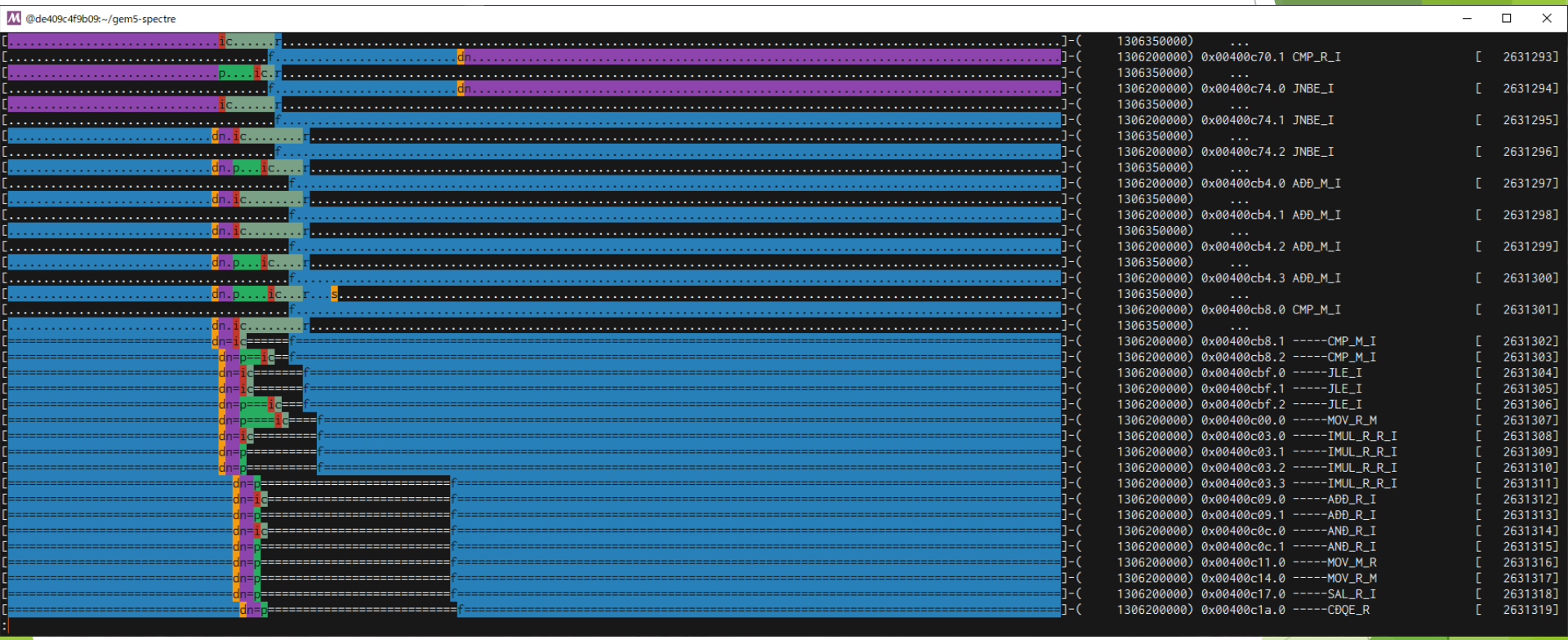
パイプラインの確認

- 以下のコマンドでパイプラインを表示

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

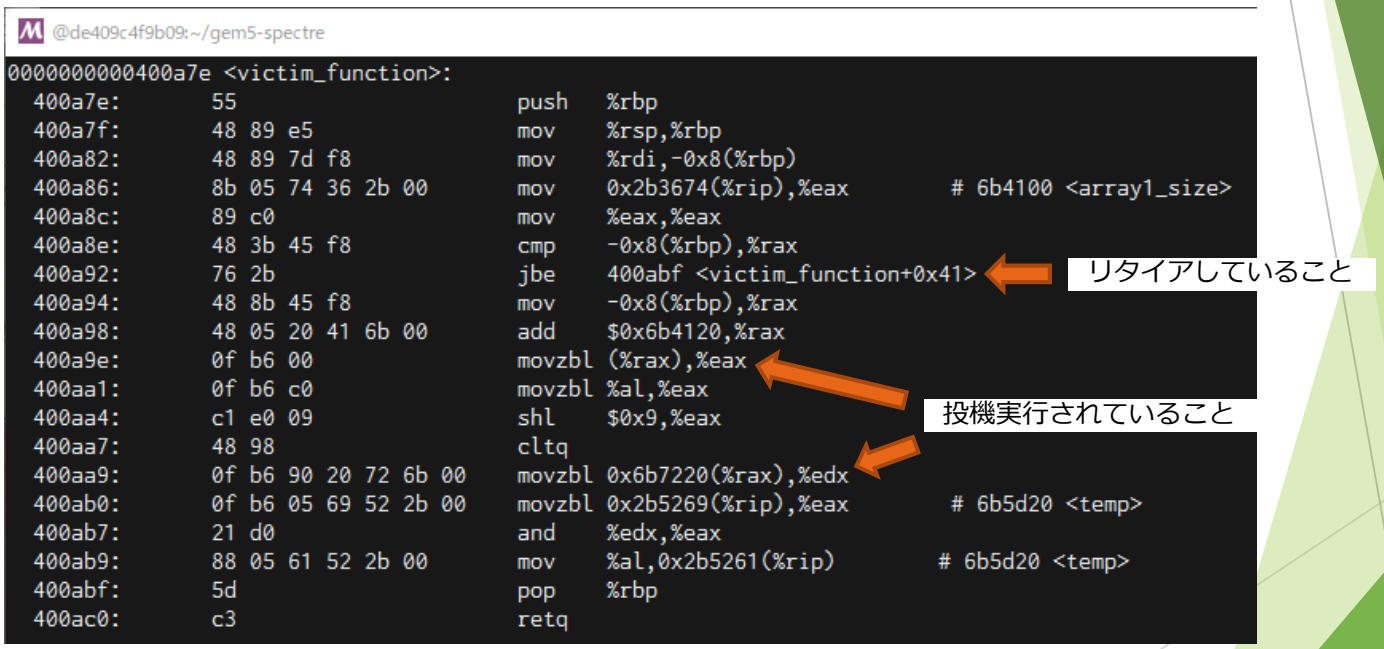


投機ミスした処理


@de409c4f9b09:~/gem5-spectre
1306350000) ...
1306200000) 0x00400c70.1 CMP_R_I [2631293]
1306350000) ...
1306200000) 0x00400c74.0 JNBE_I [2631294]
1306350000) ...
1306200000) 0x00400c74.1 JNBE_I [2631295]
1306350000) ...
1306200000) 0x00400c74.2 JNBE_I [2631296]
1306350000) ...
1306200000) 0x00400cb4.0 ADD_M_I [2631297]
1306350000) ...
1306200000) 0x00400cb4.1 ADD_M_I [2631298]
1306350000) ...
1306200000) 0x00400cb4.2 ADD_M_I [2631299]
1306350000) ...
1306200000) 0x00400cb4.3 ADD_M_I [2631300]
1306350000) ...
1306200000) 0x00400cb8.0 CMP_M_I [2631301]
1306350000) ...
1306200000) 0x00400cb8.1 -----CMP_M_I [2631302]
1306200000) 0x00400cb8.2 -----CMP_M_I [2631303]
1306200000) 0x00400cbf.0 -----JLE_I [2631304]
1306200000) 0x00400cbf.1 -----JLE_I [2631305]
1306200000) 0x00400cbf.2 -----JLE_I [2631306]
1306200000) 0x00400c00.0 -----MOV_R_M [2631307]
1306200000) 0x00400c03.0 -----IMUL_R_R_I [2631308]
1306200000) 0x00400c03.1 -----IMUL_R_R_I [2631309]
1306200000) 0x00400c03.2 -----IMUL_R_R_I [2631310]
1306200000) 0x00400c03.3 -----IMUL_R_R_I [2631311]
1306200000) 0x00400c09.0 -----ADD_R_I [2631312]
1306200000) 0x00400c09.1 -----ADD_R_I [2631313]
1306200000) 0x00400c0c.0 -----AND_R_I [2631314]
1306200000) 0x00400c0c.1 -----AND_R_I [2631315]
1306200000) 0x00400c11.0 -----MOV_M_R [2631316]
1306200000) 0x00400c14.0 -----MOV_R_M [2631317]
1306200000) 0x00400c17.0 -----SAL_R_I [2631318]
1306200000) 0x00400c1a.0 -----CDQE_R [2631319]

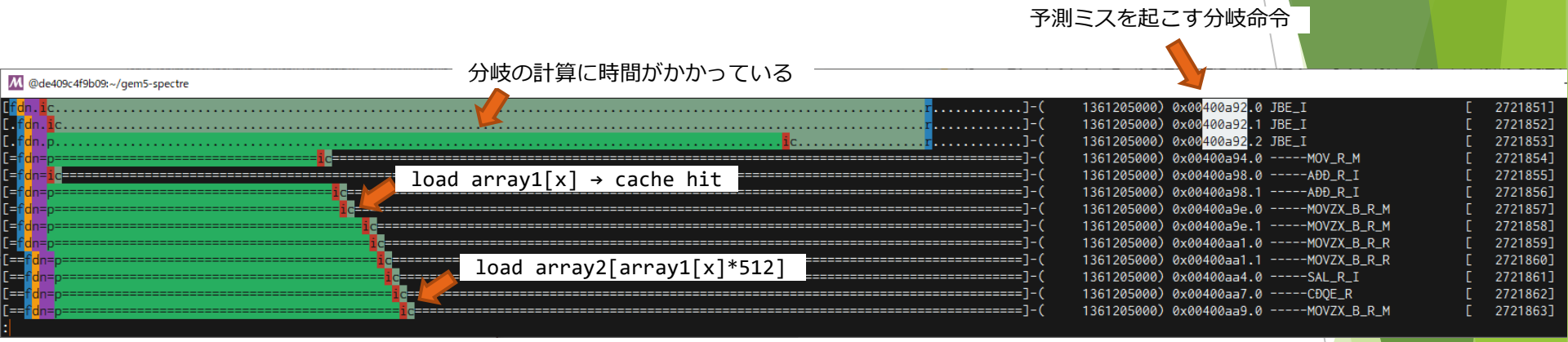
Spectreが起きている箇所

- 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



Spectreが起きている箇所

- 見つかりましたか？



- 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

- おつかれさまでした