Spectre, Meltdown, and Linux

This talk is all about the newly announced category of bugs called Spectre.

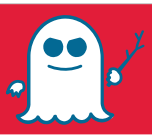
Disclaimer

- This talk vastly over-simplifies things.
- See notes for full details and resources.

https://github.com/gregkh/presentation-spectre

In order to keep this talk within the time limit, I am vastly over simplifying things.

Please see the presentation notes at the link here for more details and a full list of resources on how to find out more information about this topic.



Spectre

- Hardware bugs
- Valid code can be “tricked” into exposing sensitive data to attacking programs.
- Exploits the speculative execution model of modern CPUs.
- Many different variants.
- Is going to be with us for a very long time!

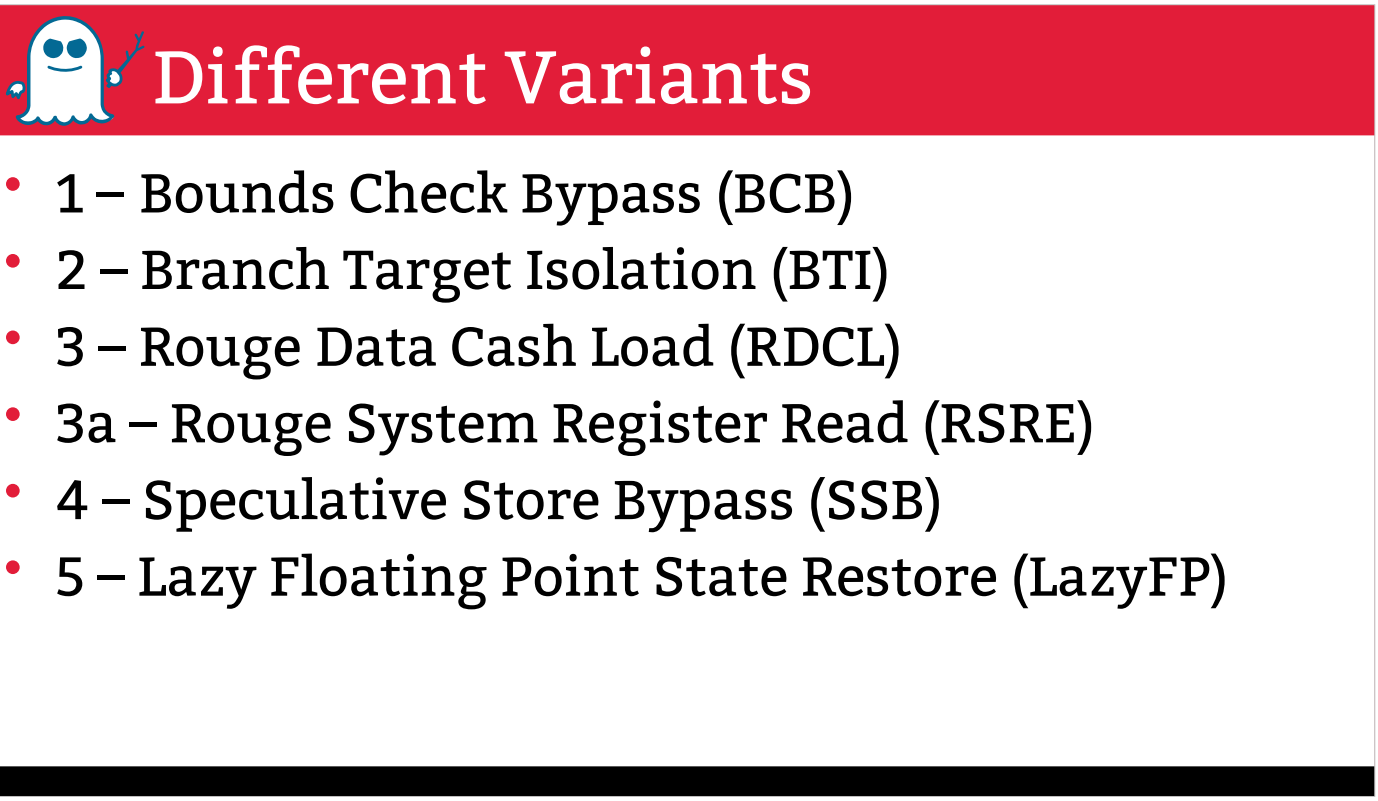
Spectre is the category of new CPU bugs that were originally discovered last year in July first by Jann Horn of Google and then independently discovered by others in the few months afterward.

These bugs are problems in the hardware itself that takes advantage of how CPUs speculatively execute code. I will describe what this means later on.

All of these bugs are ones that enable attackers to read memory of other programs or virtual machines. No memory can be modified.

There are many different variants of these bugs that have been found so far.

Due to the way that CPUs work, these problems are going to be with us for a very long time as we clean up after the mess.



Here are the different variants that have been announced so far.

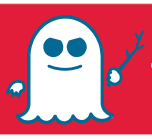
All of the variants end up doing the same thing, allowing memory to be read that should not be read, but they do it in different ways, which results in the different names.

They require different methods of protection, because they abuse different parts of the CPU in order to achieve the attack.

1, 2, and 3 were in the initial announcement, January 4, 2018

3a and 4 were made public May 21, 2018

5 “leaked” June 13, full details to be published June 27



variant 1 – Bounds check bypass

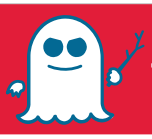
- Uses the kernel to read memory of another process or virtual machine.
- Fixed by core kernel changes.
- Lots of individual drivers still need to be fixed.

Like I said earlier, all of the variants allow memory to be read from places that should not be readable. Examples of this is reading memory of the kernel itself, or different programs running in the same machine, or even reading memory of a different virtual machine.

Because of this, these bugs can be exploited by browers running scripts that can read data from other programs or tabs, or in a virtual machine to read data from different customer's virtual machines on the same server.

The first variant uses correct code in the kernel to read the memory of another program.

It was fixed by changing some core parts of the kernel, but also requires all drivers to be audited and changed as well. That work has only just started.



variant 1 – vulnerable code

```
int load_array(int *array, unsigned int user_value)
{
      if (user_value >= MAX_SIZE)
            return 0;

      return array[user_value];
}
```

This is an example of kernel code that is completely correct as written.

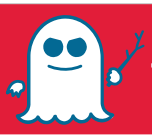
Spectre uses this correct code to take advantage of the CPU's behavior in trying to guess what the code is going to do in the future.

If you call this code a lot, the CPU learns that the check will succeed so it gets smart and preloads the value that array+user_value to be returned.

If you suddenly pass in a very large number for user_value, the CPU will preload the array+user_value memory location while it is still doing the check on the first line. When that check fails, the CPU will "stall" and unwind itself and return the error value and process continues on correctly.

But, that invalid memory location was read by the CPU and placed in the cache already. This can then be detected by a program running elsewhere in order to determine exactly what that memory value was.

Doing this is not fast, you can end up reading 2000 bytes a second, but that's all you need, you now have access to memory values you should not have access to.



variant 1 – fixed code

```
int load_array(int *array, unsigned int user_value)
{
      if (user_value >= MAX_SIZE)
            return 0;

      user_value = array_index_nospec(user_value, MAX_SIZE);

      return array[user_value];
}
```

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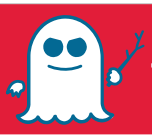

variant 1 – fixed code

```
#define array_index_nospec(index, size)                                 \
({                                                                      \
        typeof(index) _i = (index);                                     \
        typeof(size) _s = (size);                                       \
        unsigned long _mask = array_index_mask_nospec(_i, _s);\
                                                                        \
        BUILD_BUG_ON(sizeof(_i) > sizeof(long));                        \
        BUILD_BUG_ON(sizeof(_s) > sizeof(long));                        \
                                                                        \
        (typeof(_i)) (_i & _mask);                                      \
})
```

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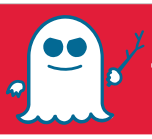
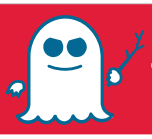


variant 1 – fixed code - x86

```
static inline unsigned long
      array_index_mask_nospec(unsigned long index,
                              unsigned long size)
{
      unsigned long mask;

      asm ("cmp %1,%2; sbb %0,%0;"
                     :"=r" (mask)
                     :"g"(size),"r" (index)
                     :"cc");
      return mask;
}
```

This is an example of kernel code that is completely correct as written.



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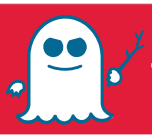
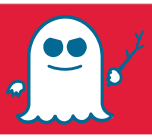


variant 1 – Fix dates*

- x86
  - 4.14.14 17 January 2018
  - 4.9.77 17 January 2018
  - 4.4.113 23 January 2018
- ARM
  - 4.15.4 17 February 2018
  - 4.14.21 22 February 2018

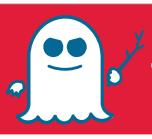
This is an example of kernel code that is completely correct as written.



*Fixes keep coming

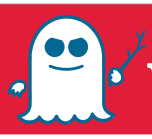
- These are the “first fixed” dates.
- Later kernels get more fixes and improvements.
- Keep updating your kernel & microcode!

This is an example of kernel code that is completely correct as written.



variant 1 – Fix dates again

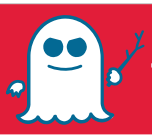
- x86
  - 4.16.11 22 May 2018
  - 4.14.43 22 May 2018
  - 4.9.102 22 May 2018
- ARM
  - 4.16 1 April 2018
  - 4.9.95 20 April 2018



variant 2 – Branch target injection

- Abuses the CPU branch predictor.
- Read data from kernel or other virtual machine.
- Fixed by compiler, kernel, & microcode updates.
- “retpoline”

This is an example of kernel code that is completely correct as written.

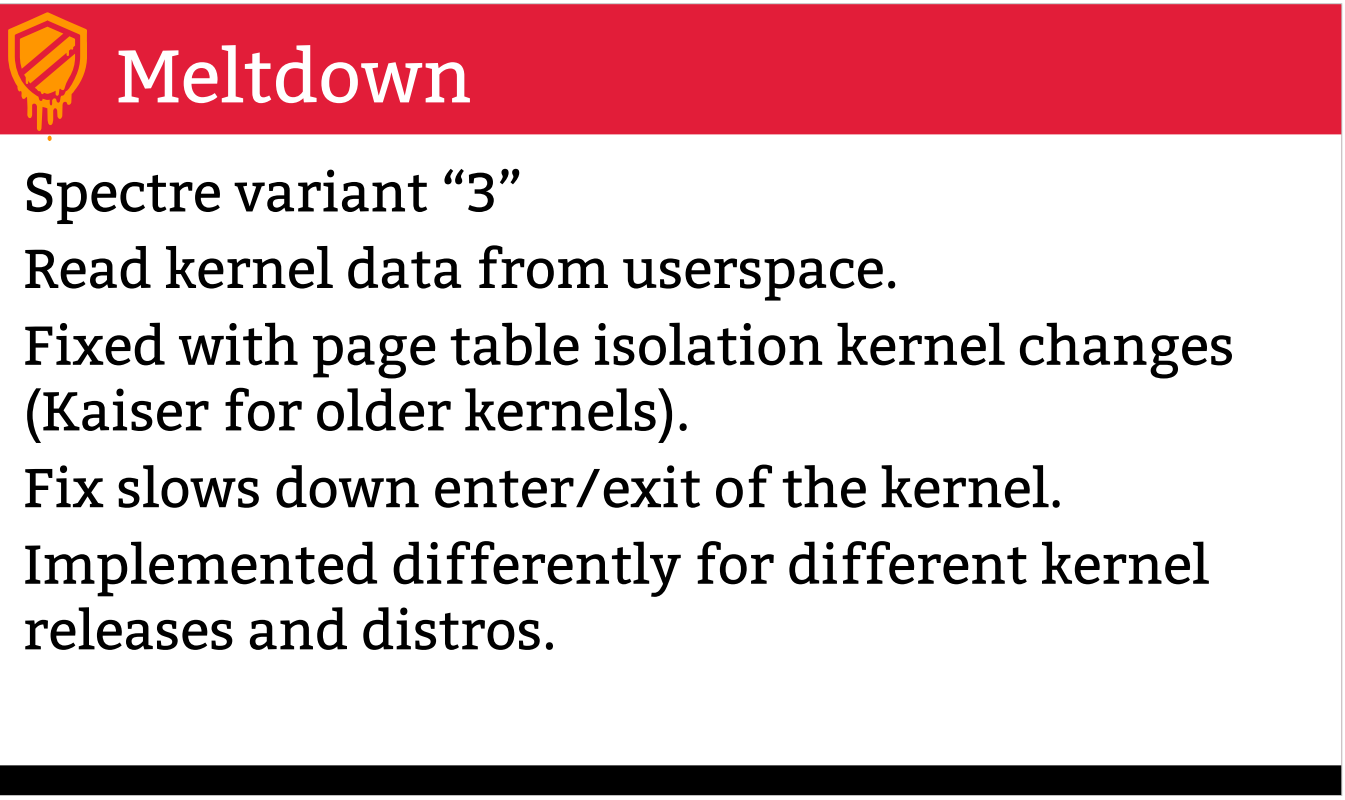


variant 2 – Fix dates*

- x86
  - 4.15.9 11 March 2018
  - 4.14.26 11 March 2018
  - 4.9.87 11 March 2018
  - 4.4.121 11 March 2018

*More fixes and optimizations happened in later kernels

This is an example of kernel code that is completely correct as written.



This is variant “3” of spectre

It allows a userspace program to be able to read data from within the kernel

It is fixed with a large number of kernel patches that implement “page table isolation”. This moves all kernel memory outside of the system when entering/exiting userspace, preventing userspace from being able to see kernel memory entirely.

The “Kaiser” paper first suggested this solution for a different type of kernel vulnerability, and this is what it is sometimes called

It slows down every time you enter or exit the kernel from userspace, which means that processes that do a lot of I/O accesses are hit hard.

Meltdown – fix dates

- x86
  - 4.14.11 02 January 2018
  - 4.9.75 05 January 2018
  - 4.4.110 05 January 2018
- ARM
  - 4.15.4 17 February 2018
  - 4.14.20 17 February 2018
  - 4.9.93 08 April 2018

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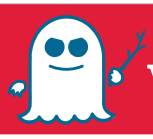
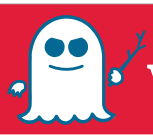
variant 3a – Rouge system register read

- Abuses the reading of system registers.
- Read data from kernel or other virtual machine.
- Kernel fix for Meltdown solves this problem.



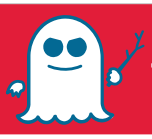
variant 4 – Speculative Store Bypass

- Can execute and read beyond what is expected.
- Read data from kernel or other virtual machine.
- Minor kernel changes.
- Microcode update required for full protection.



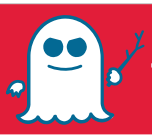
variant 4 – Speculative Store Bypass

- x86
  - 4.16.11 22 May 2018
  - 4.14.43 22 May 2018
  - 4.9.102 22 May 2018



variant 5 – Lazy FP state restore

- Uses the old “lazy floating point restore” method to read memory of another process or virtual machine.
- Details to be published June 27.
- Linux kernel fixed in 2016.



variant 5 – Fix dates

- x86
  - 4.6 15 May 2016
  - 4.4.138 16 June 2018

Why this is such a big deal

- CPU bugs require software & microcode fixes.
- All operating systems are affected.
- Performance will decrease.
- Totally new class of vulnerabilities.
- We will be finding, and fixing, these for a very long time.

Linux's response

- Companies were notified, but not developers.
- Developers notified very late, resulting in delay of fixes.
- Majority of the world runs non-corporate kernels.
- Intel is now working with some developers.

Keeping a secure system

- Take ALL stable kernel updates.
  - Do **NOT** cherry-pick patches.
- Enable hardening features.
- Update to a newer major kernel version where ever possible.
- Update your microcode/BIOS!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