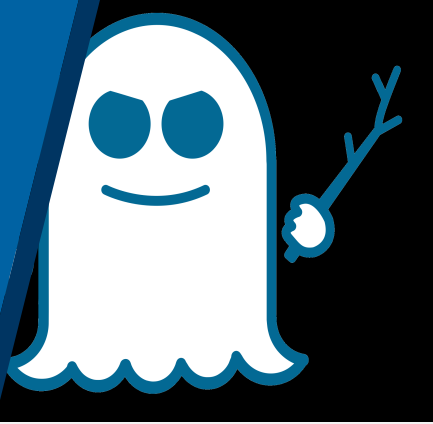
Spectre Attacks: Exploiting Speculative Execution

and why the heck is the computer speculating anyway?



Werner Haas

April 14, 2021

CYBERUS TECHNOLOGY

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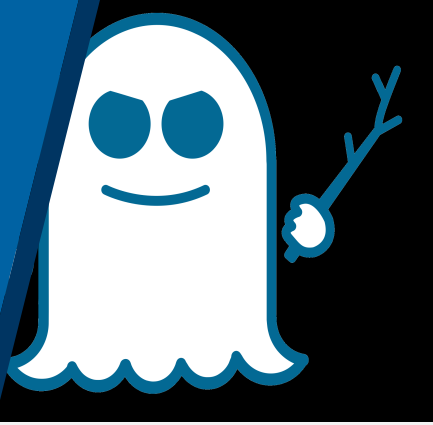

Paul Kocher, Jann Horn, Anders Fogh, Daniel Genkin,
Daniel Gruss, Mike Hamburg, Moritz Lipp, Stefan Mangard,
Thomas Prescher, Michael Schwarz, Yuval Yarom

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Iron Law of Processor Performance

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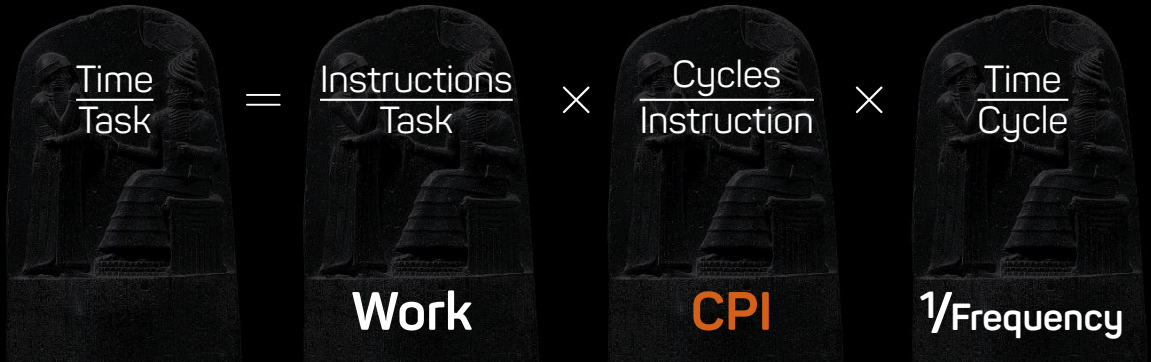
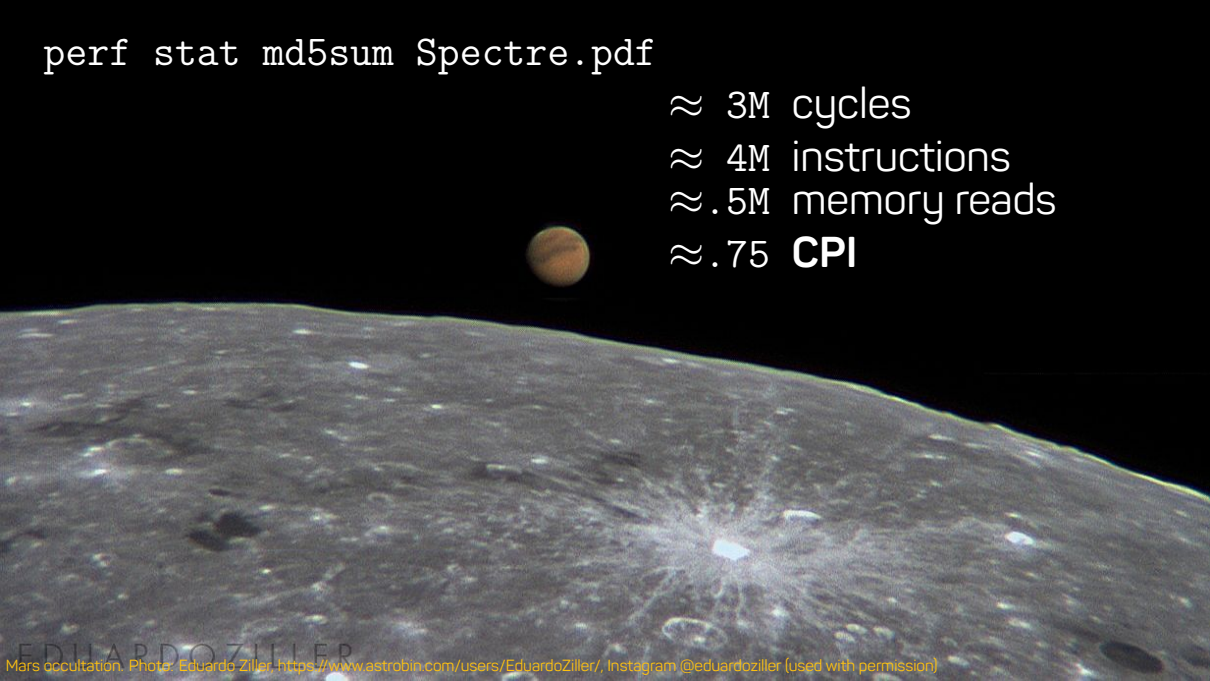


perf stat md5sum Spectre.pdf

Mars occultation. Photo: Eduardo Ziller-https://www.astrobin.com/users/EduardoZiller/, Instagram @eduardoziller (used with permission)

```
perf stat md5sum Spectre.pdf
```

≈ 3M cycles
≈ 4M instructions
≈.5M memory reads
≈.75 **CPI**

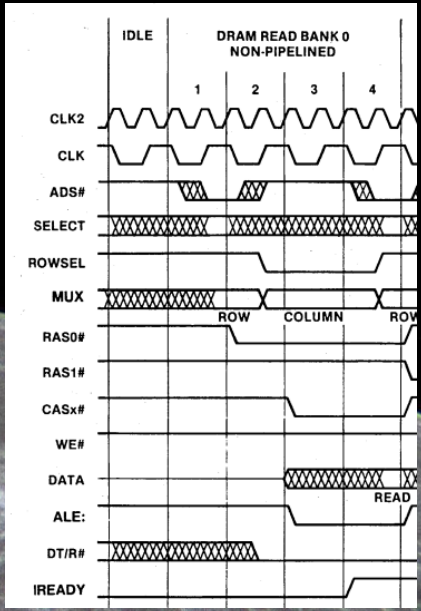


Mars occultation. Photo: Eduardo Ziller-https://www.astrobin.com/users/EduardoZiller/, Instagram @eduardoziller (used with permission)

intel

INTEL386™ DX MICROPROCESSOR

HARDWARE REFERENCE MANUAL



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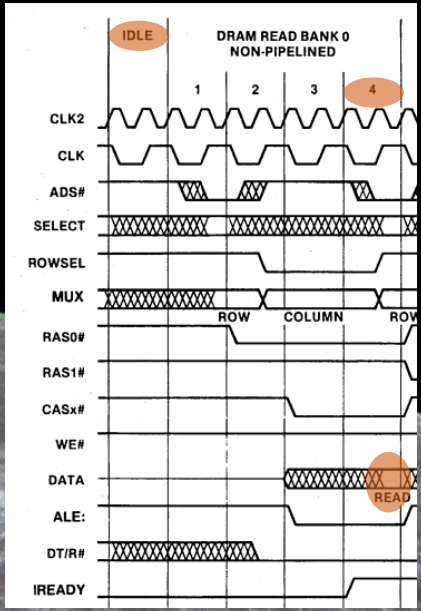

Mars occultation. Photo: Eduardo Ziller- https://www.astrobin.com/users/EduardoZiller/, Instagram @eduardoziller (used with permission)

Technology Evolution

Frequency	20 MHz	→	2 GHz
Instructions	4 M		4 M
Memory reads	.5 M		.5 M
Latency [cycles]	4		
Cycles	3 M		
CPI	0,75		

Hubble sees a smiling lens, Image credit: NASA/ESA

Technology Evolution

Frequency	20 MHz	→	2 GHz
Instructions	4 M		4 M
Memory reads	.5 M		.5 M
Latency [cycles]	4		>100
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Technology Evolution

Frequency	20 MHz	→	2 GHz
Instructions	4 M		4 M
Memory reads	.5 M		.5 M
Latency [cycles]	4		>100
Cycles	3 M		>53 M
CPI	0,75		

Hubble sees a smiling lens, Image credit: NASA/ESA

Technology Evolution

Frequency	20 MHz	→	2 GHz
Instructions	4 M		4 M
Memory reads	.5 M		.5 M
Latency [cycles]	4		>100
Cycles	3 M		>53 M
CPI	0,75	→	>13,25

Hubble sees a smiling lens, Image credit: NASA/ESA

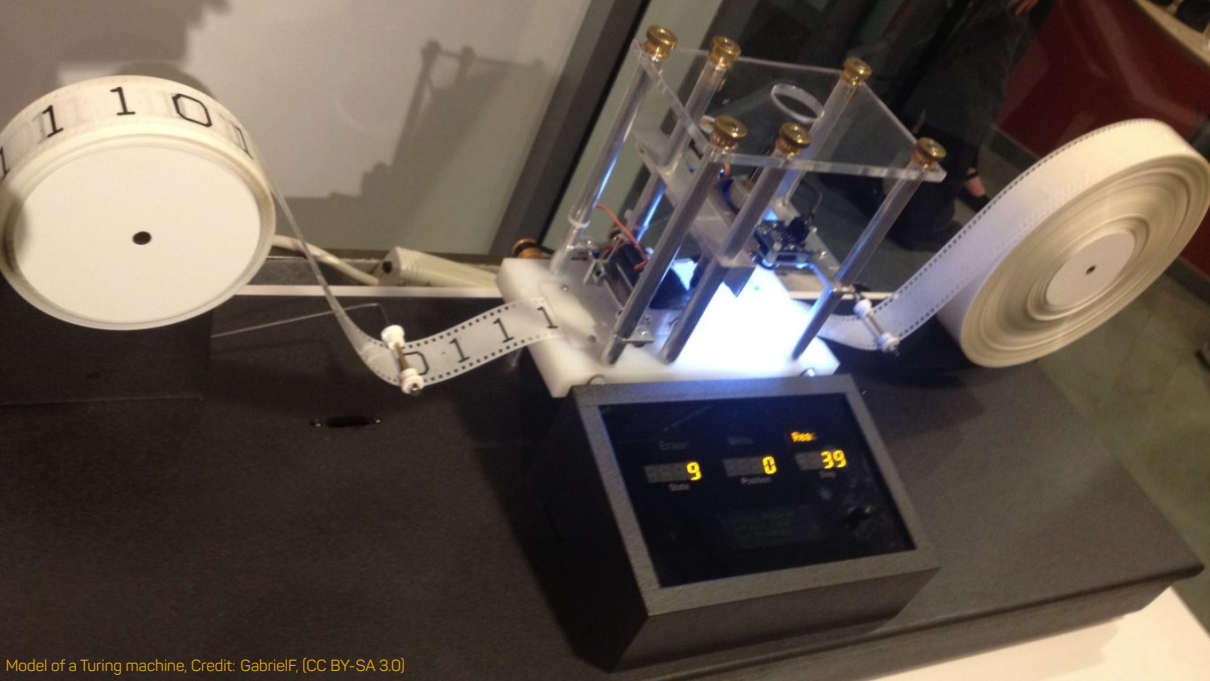
Technology Evolution

Frequency	20 MHz	→	2 GHz	100x
Instructions	4 M		4 M	
Memory reads	.5 M		.5 M	
Latency [cycles]	4		>100	
Cycles	3 M		>53 M	
CPI	0,75	→	>13,25	>17x

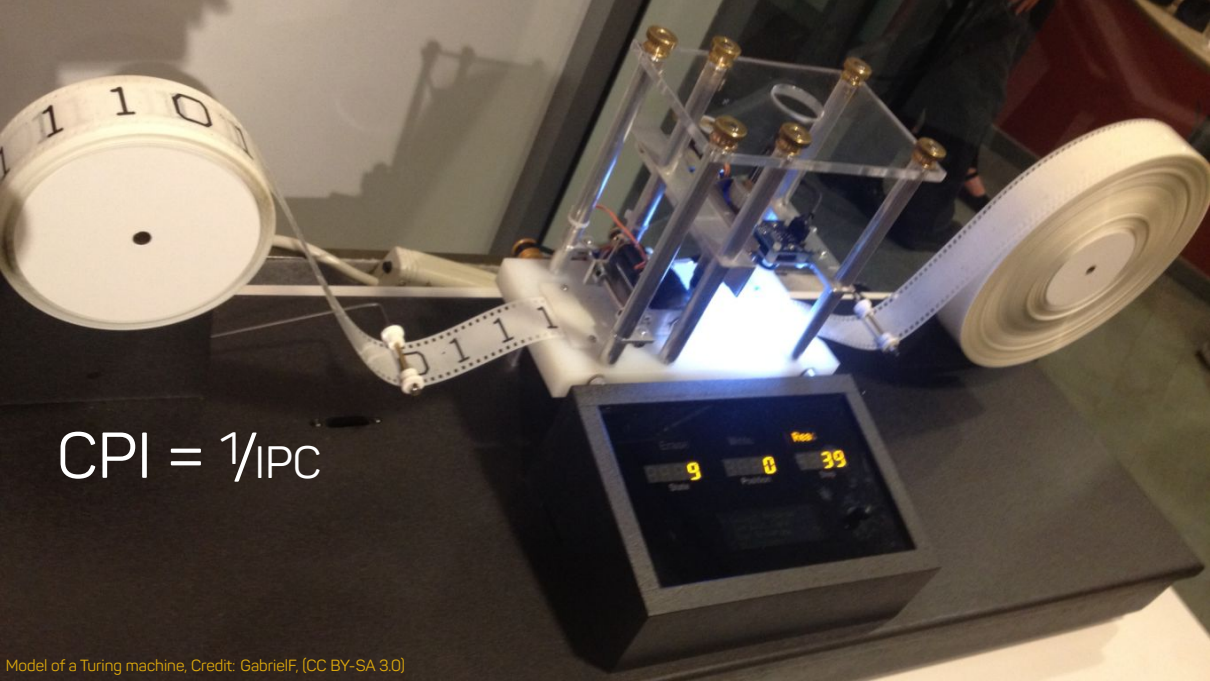
Hubble sees a smiling lens, Image credit: NASA/ESA

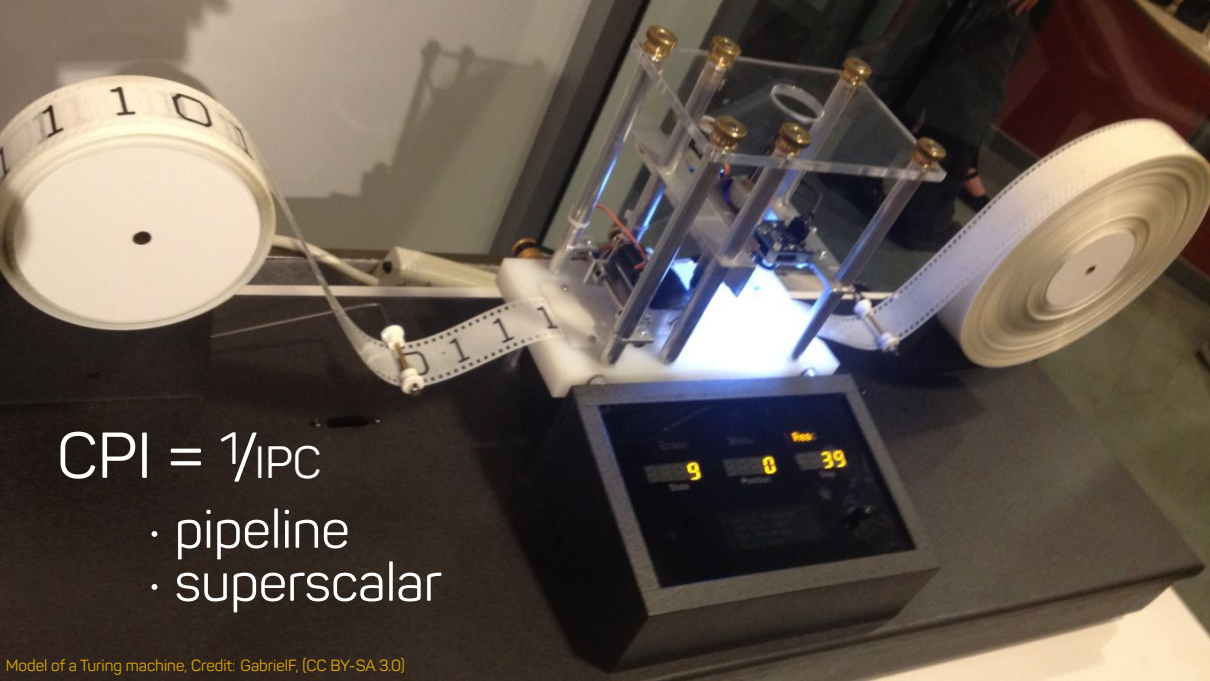
Technology Evolution

Hubble sees a smiling lens, Image credit: NASA/ESA



Model of a Turing machine, Credit: GabrielF, (CC BY-SA 3.0)


CPI = 1/IPC
Model of a Turing machine, Credit: GabrielF, (CC BY-SA 3.0)



CPI = 1/IPC

- pipeline
- superscalar

Model of a Turing machine, Credit: GabrielF, (CC BY-SA 3.0)

```
# Pad with 0s to get 512b chunks
while len(message)%512 != 448:
  message.append(0)
```

Perseverance is Roving on Mars, Image credit: NASA/JPL-Caltech

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jump instr.	detection	destination
direct	@decode	calculation

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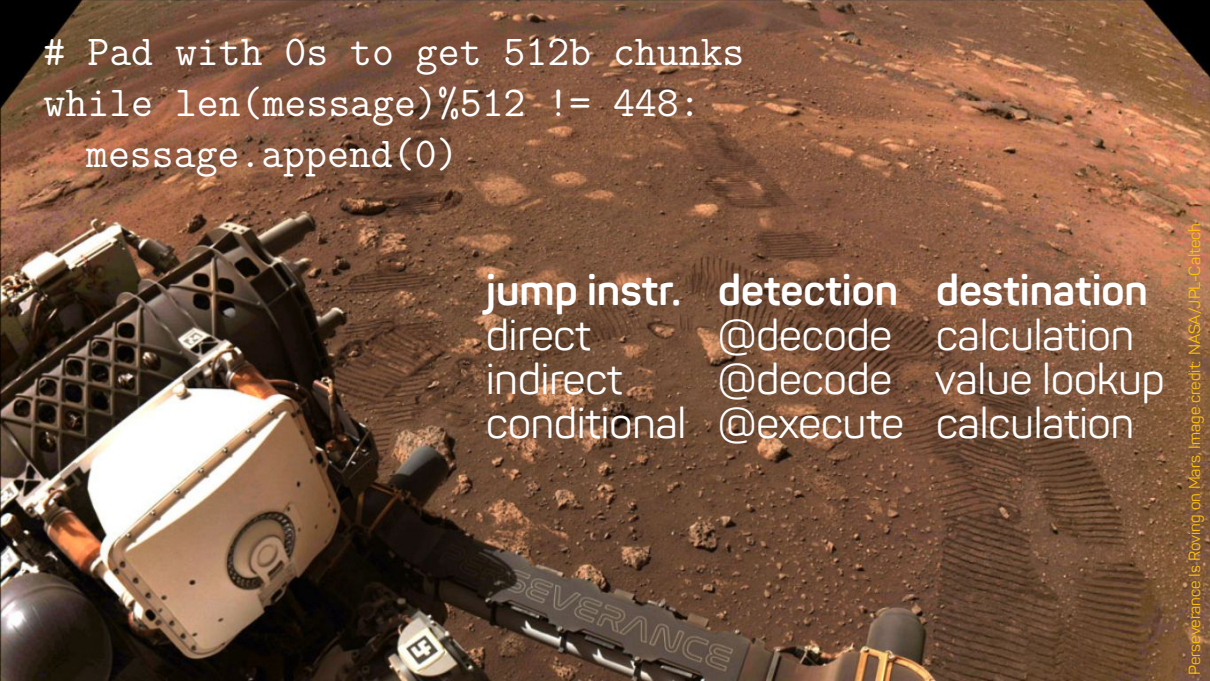

jump instr.	detection	destination
direct	@decode	calculation
indirect	@decode	value lookup
conditional	@execute	calculation

Perseverance is Roving on Mars, Image credit: NASA/JPL-Caltech

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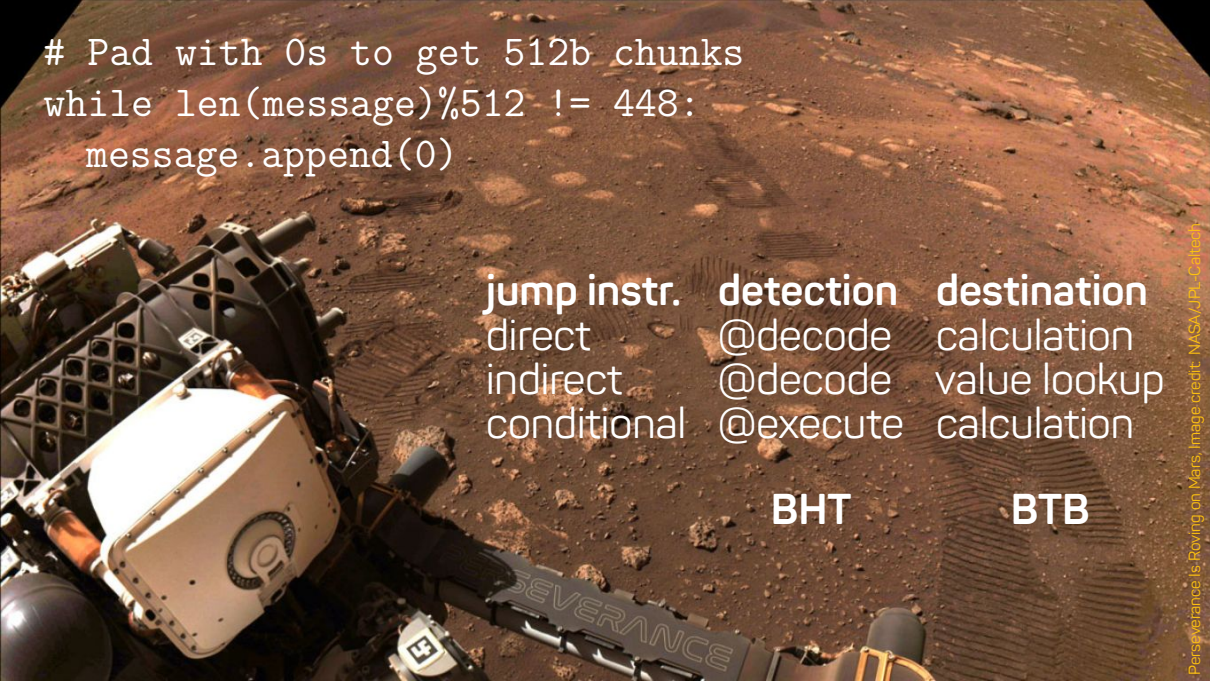

jump instr.	detection	destination
direct	@decode	calculation
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BHT **BTB**

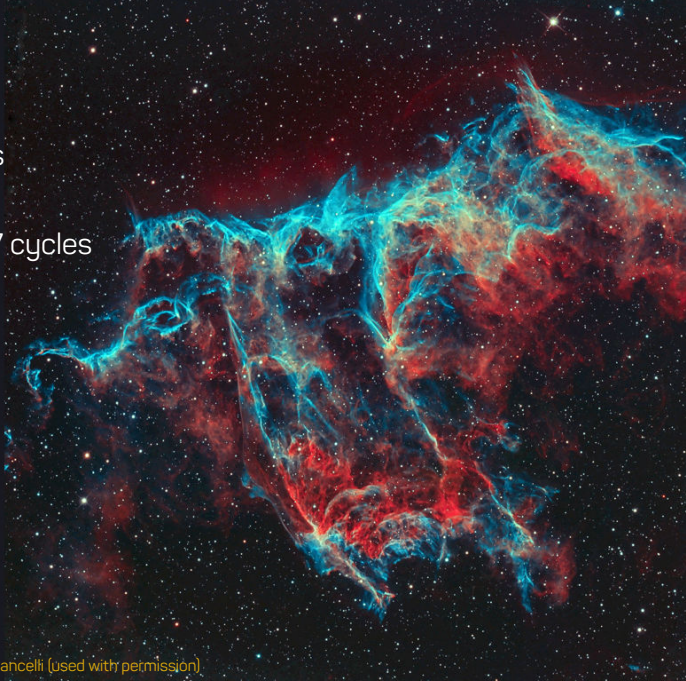
Perseverance is Roving on Mars, Image credit: NASA/JPL-Caltech

Spectre

backyardastronomer.com: Spooky. Image credit: Paul Mortfield & Stefano Cancelli (used with permission)

Spectre v1: BHT

- SPEC CPU 2017: ≈ 20% branches
- Intel Ice Lake: 5-way decode
- Branch misprediction penalty ≈ 17 cycles



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Spectre v1: BHT

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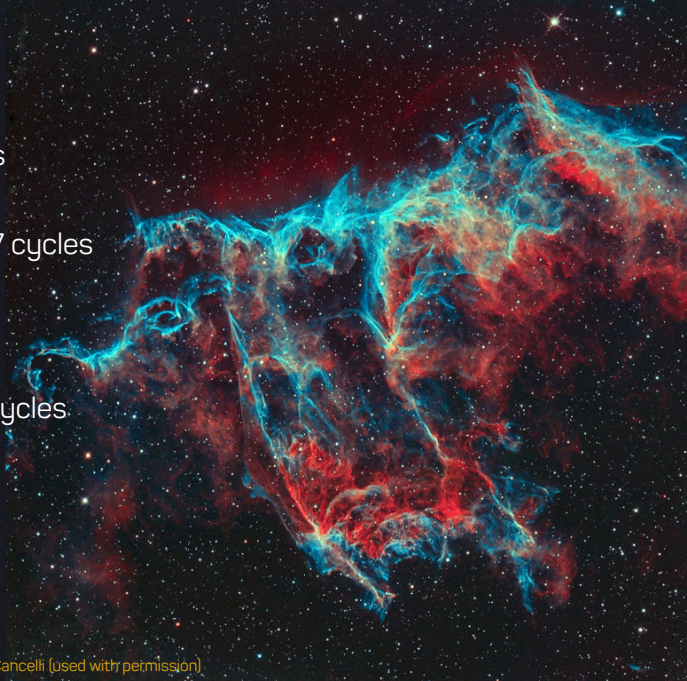
Time to fetch 1000 instructions

- perfect prediction:
  1000 instructions / $^{5}/_{\text{cycle}}$ = 200 cycles



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Time to fetch 1000 instructions

- perfect prediction:
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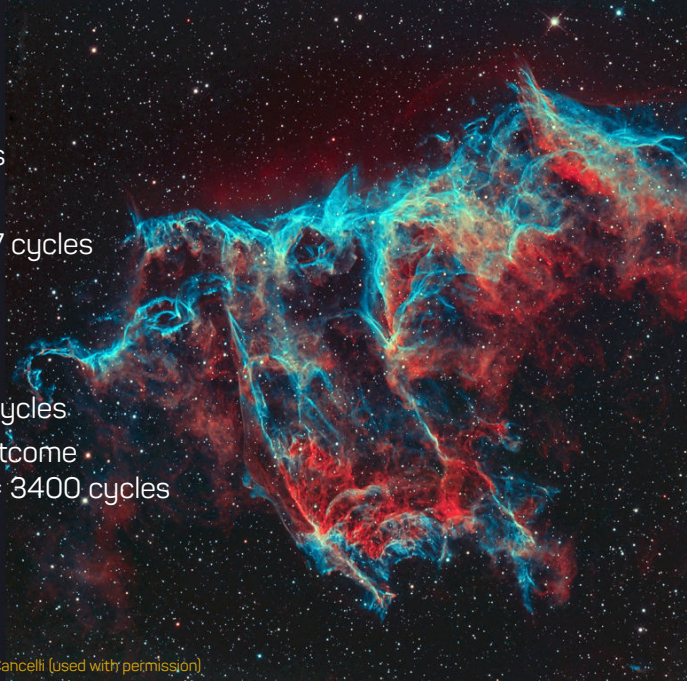
- no speculation: wait for branch outcome
  1000 instructions / 5 · 17 cycles = 3400 cycles



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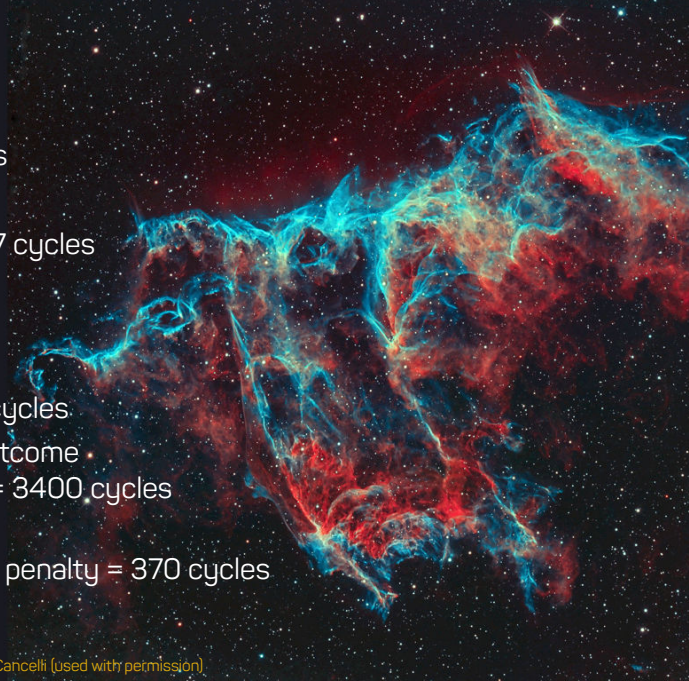
Spectre v1: BHT

- SPEC CPU 2017: ≈ 20% branches
- Intel Ice Lake: 5-way decode
- Branch misprediction penalty ≈ 17 cycles

Time to fetch 1000 instructions

- perfect prediction:
  1000 instructions / $^{5}/_{\text{cycle}}$ = 200 cycles
- no speculation: wait for branch outcome
  1000 instructions / 5 · 17 cycles = 3400 cycles
- 99% accuracy:
  200 cycles + 10 misses · 17 cycle penalty = 370 cycles

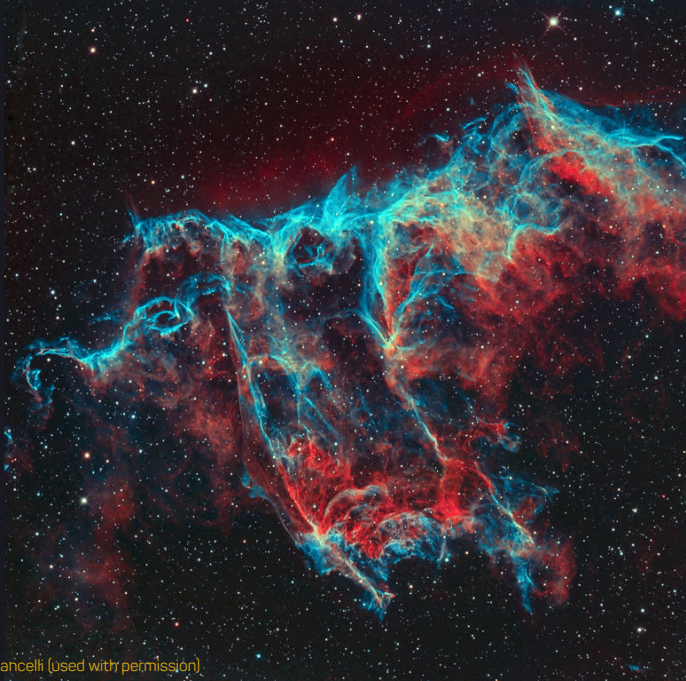


backyardastronomer.com: Spooky, Image credit: Paul Mortfield & Stefano Cancelli (used with permission)

Spectre v2: BTB

Branch predictor hot spot

- every cycle
- every instruction



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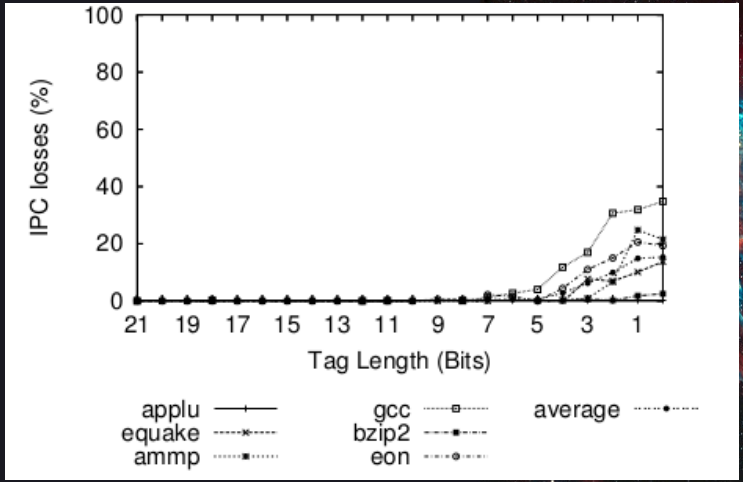
Spectre v2: BTB



Tomas et al.: Reducing the Number of Bits in the BTB to Attack the Branch Predictor Hot-Spot, Euro-Par 2008

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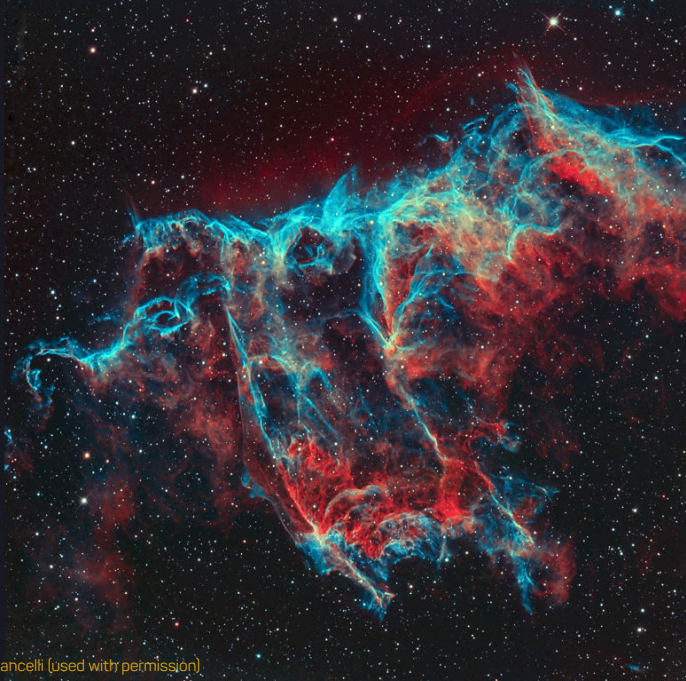
Spectre



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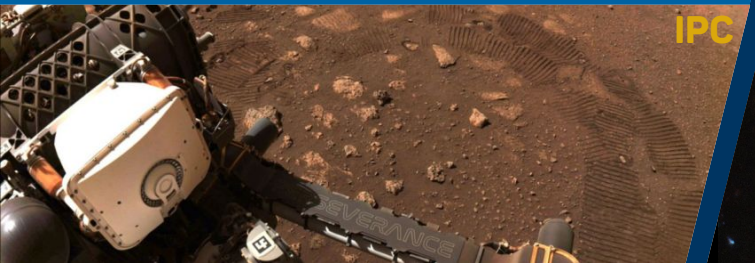
Iron Law

Iron Law

CPI



IPC

Iron Law

CPI

Spectre

Iron Law

IPC

CPI