Mobile CPU's Rise to Power:
Quantifying the Impact of Generational Mobile CPU Design Trends on Performance, Energy, and User Satisfaction

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NOKIA
1
2 abc
3 def
4 ghi
5 jkl
6 mno
7 pqrs
8 tuv
9 wxyz
*
0
#

NOKIA
1
2 abc
3 def
4 ghi
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6 mno
7 pqrs
8 tuv
9 wxyz
*
0
#

Snake

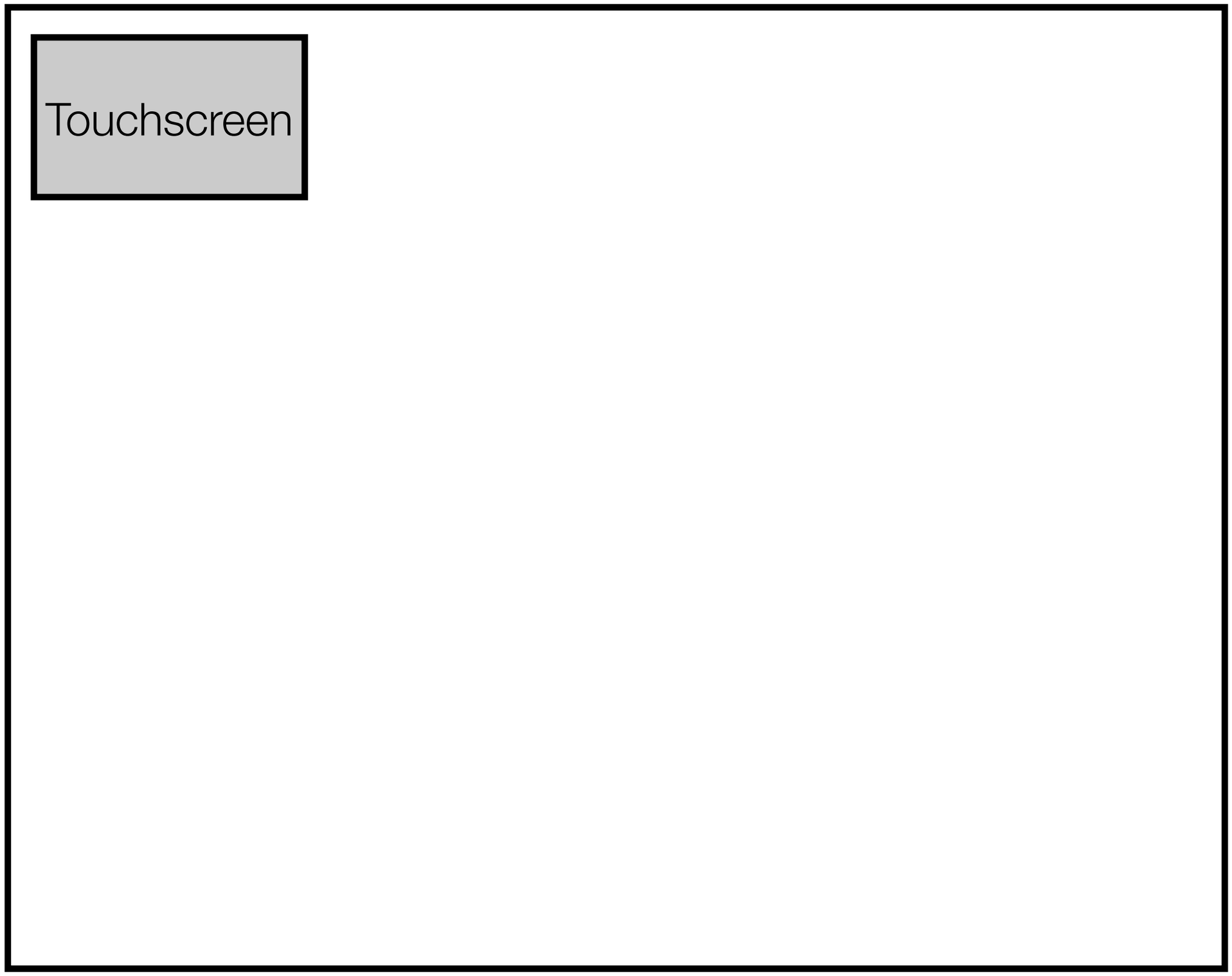
2000

Snake
2000

Snake Simulator
2016

Mobile Device

Mobile Device



Mobile Device

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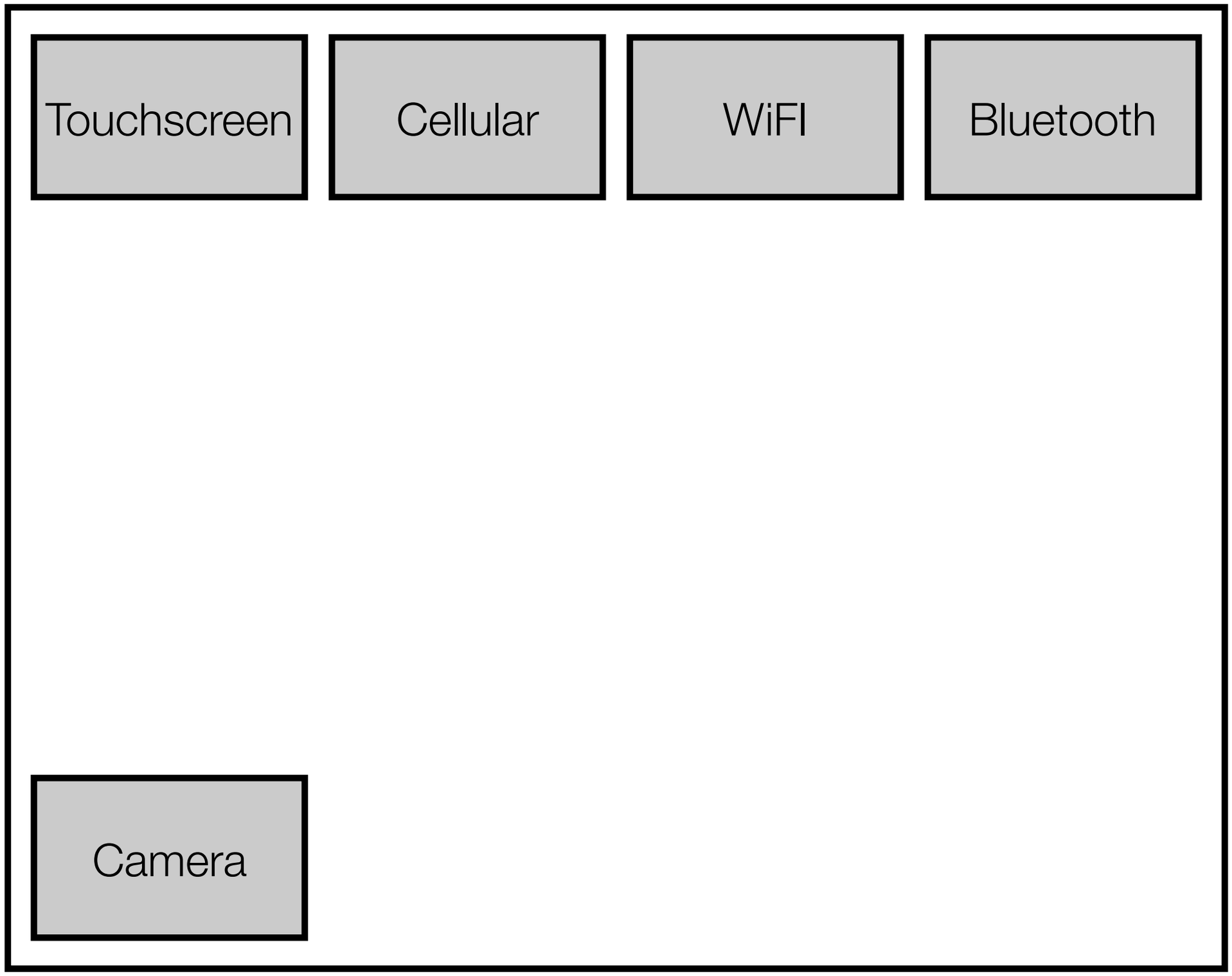
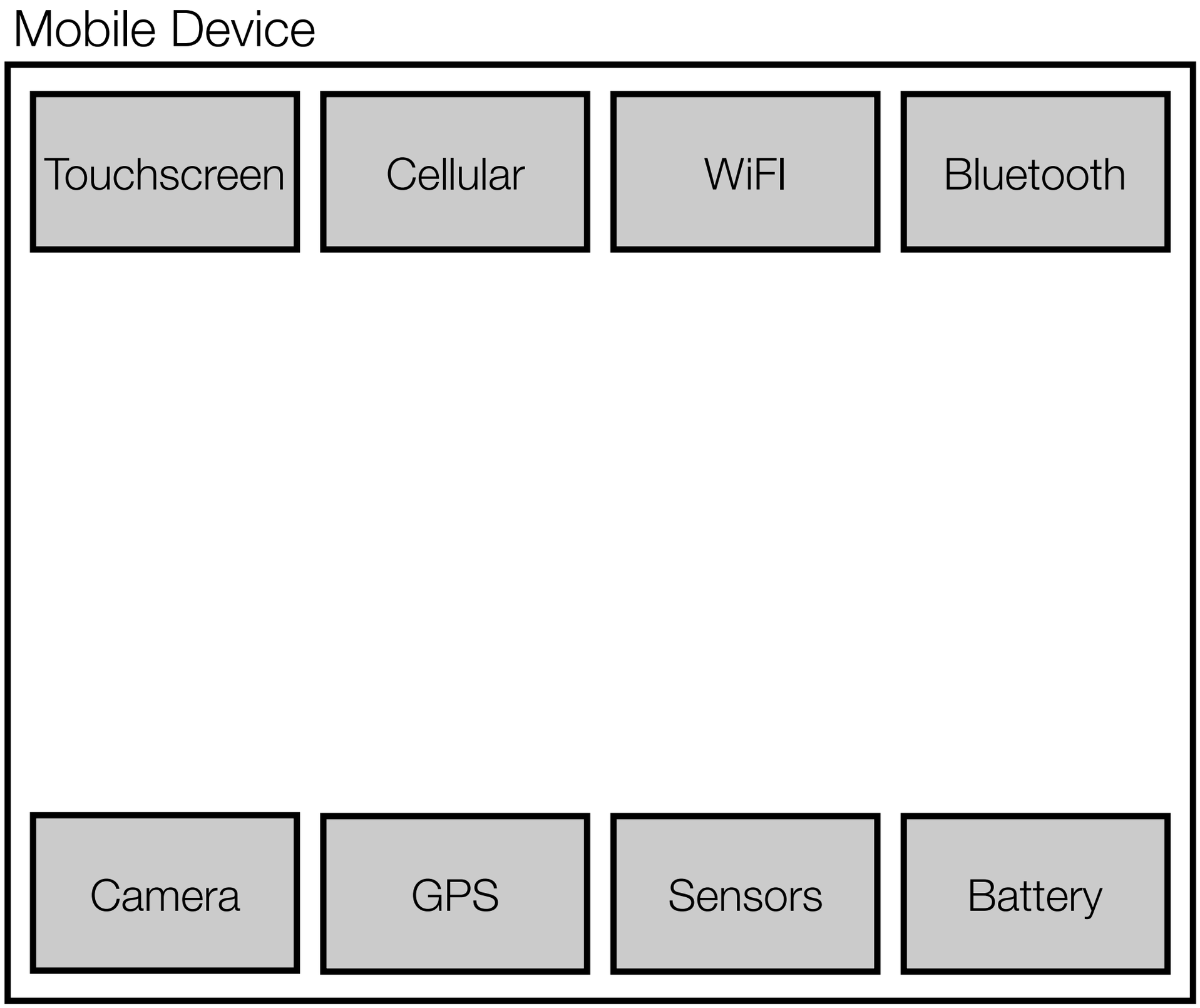
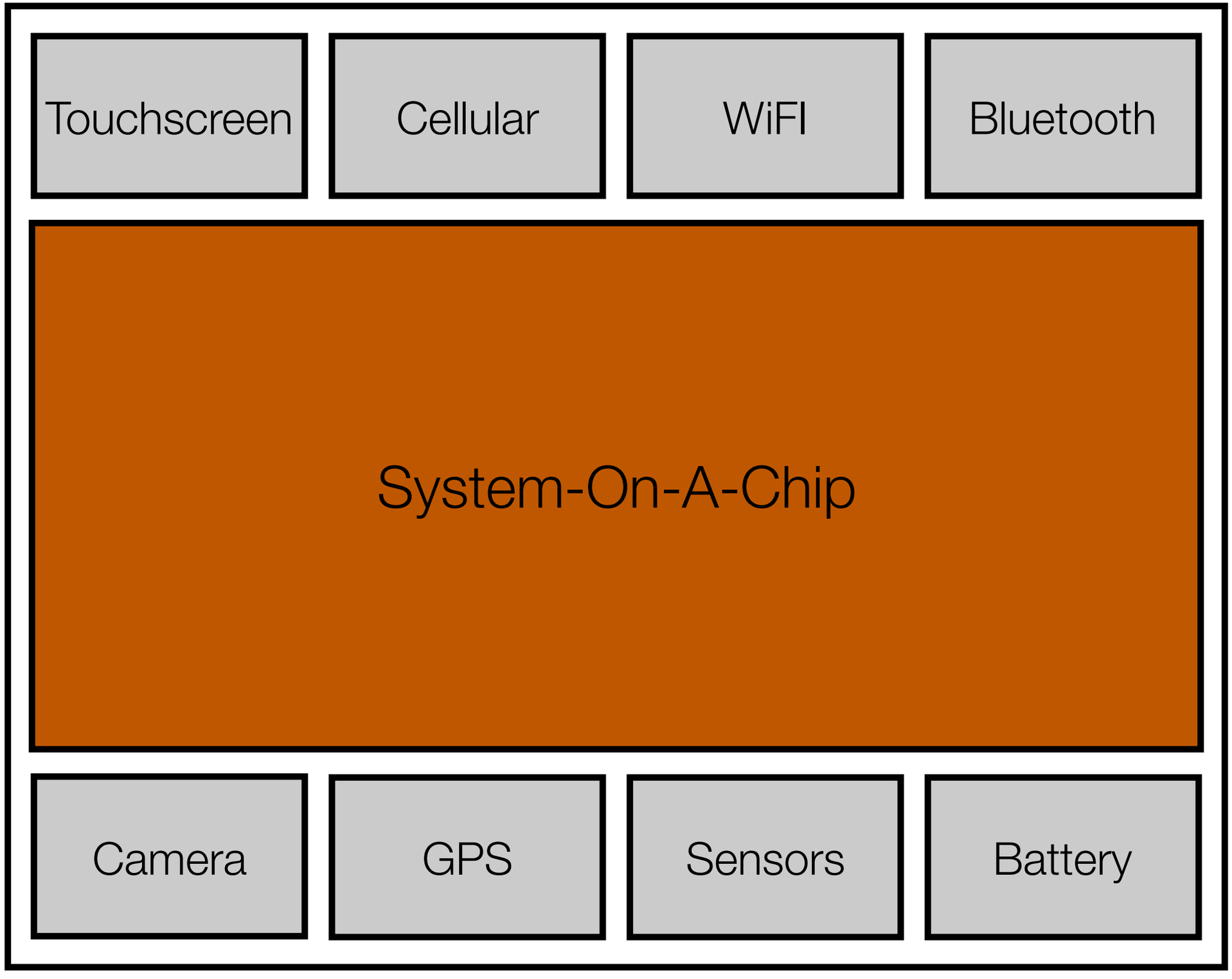
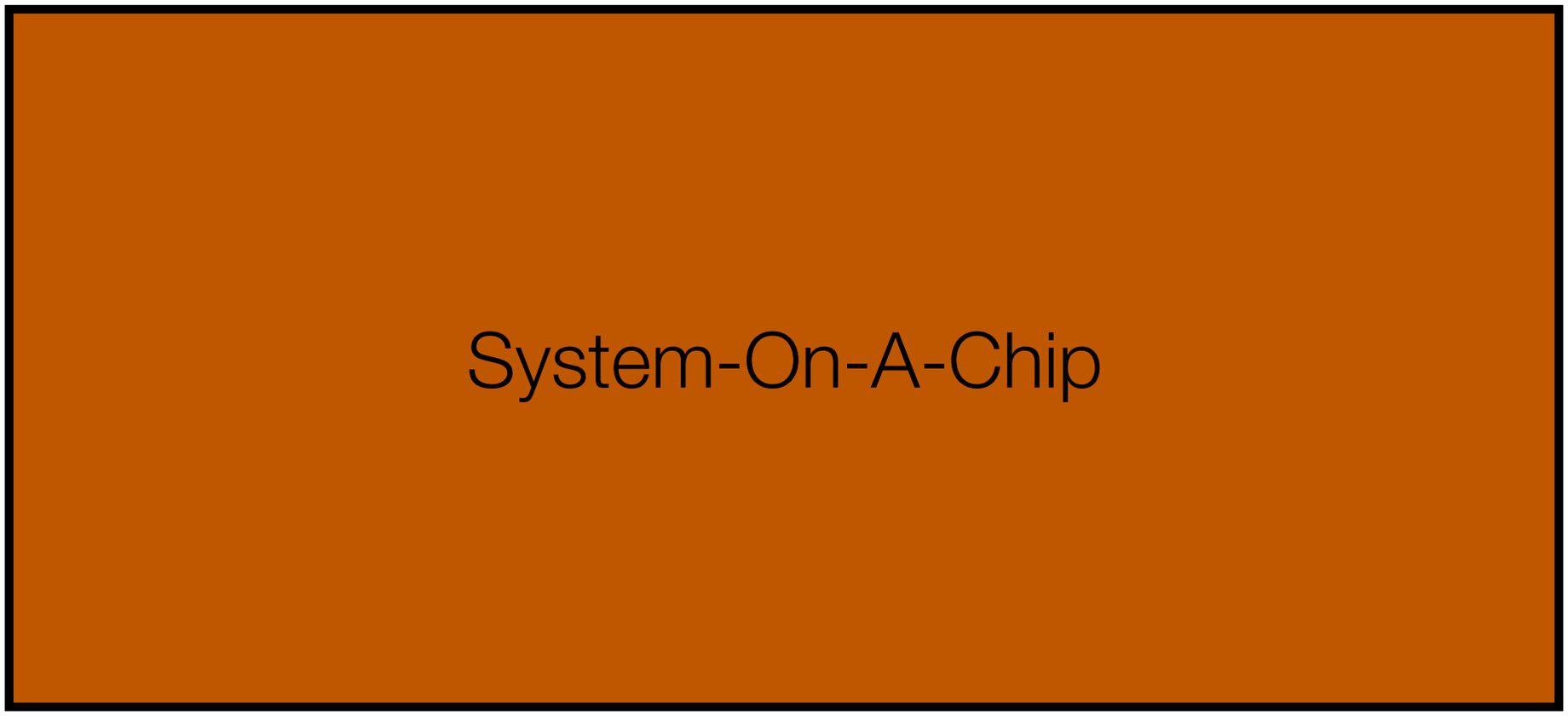



Mobile Device
Touchscreen
Cellular
WiFI
Bluetooth
Camera
GPS
Sensors
Battery

Mobile Device




System-On-A-Chip

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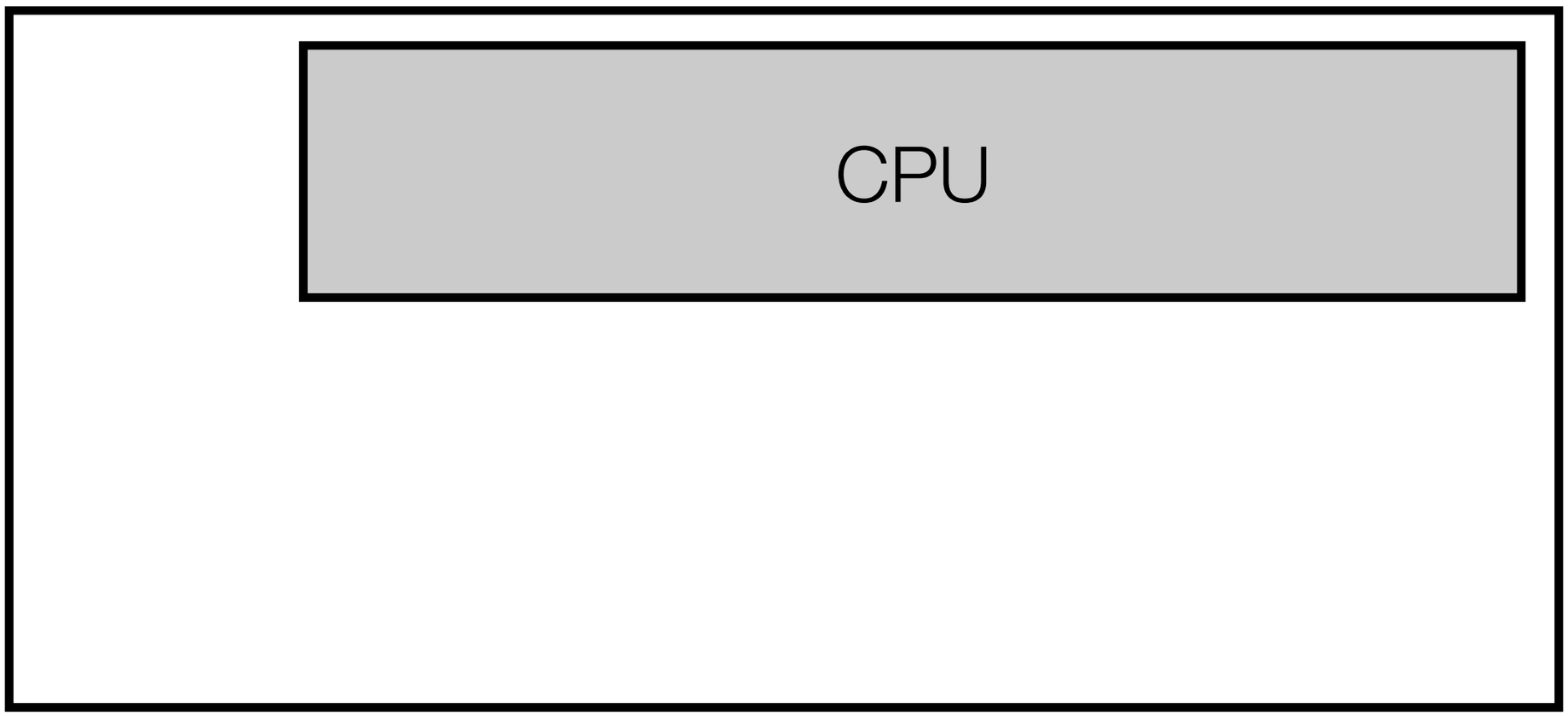

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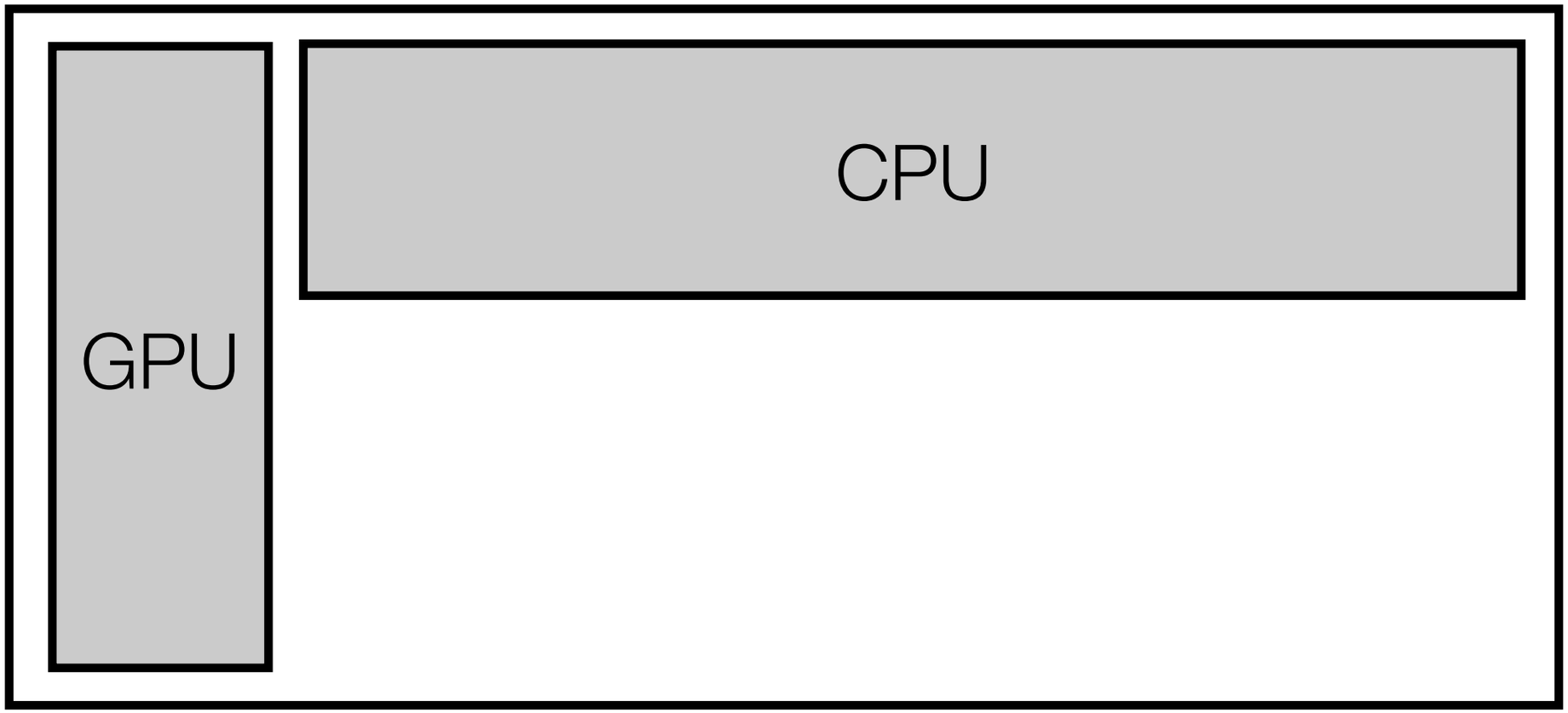

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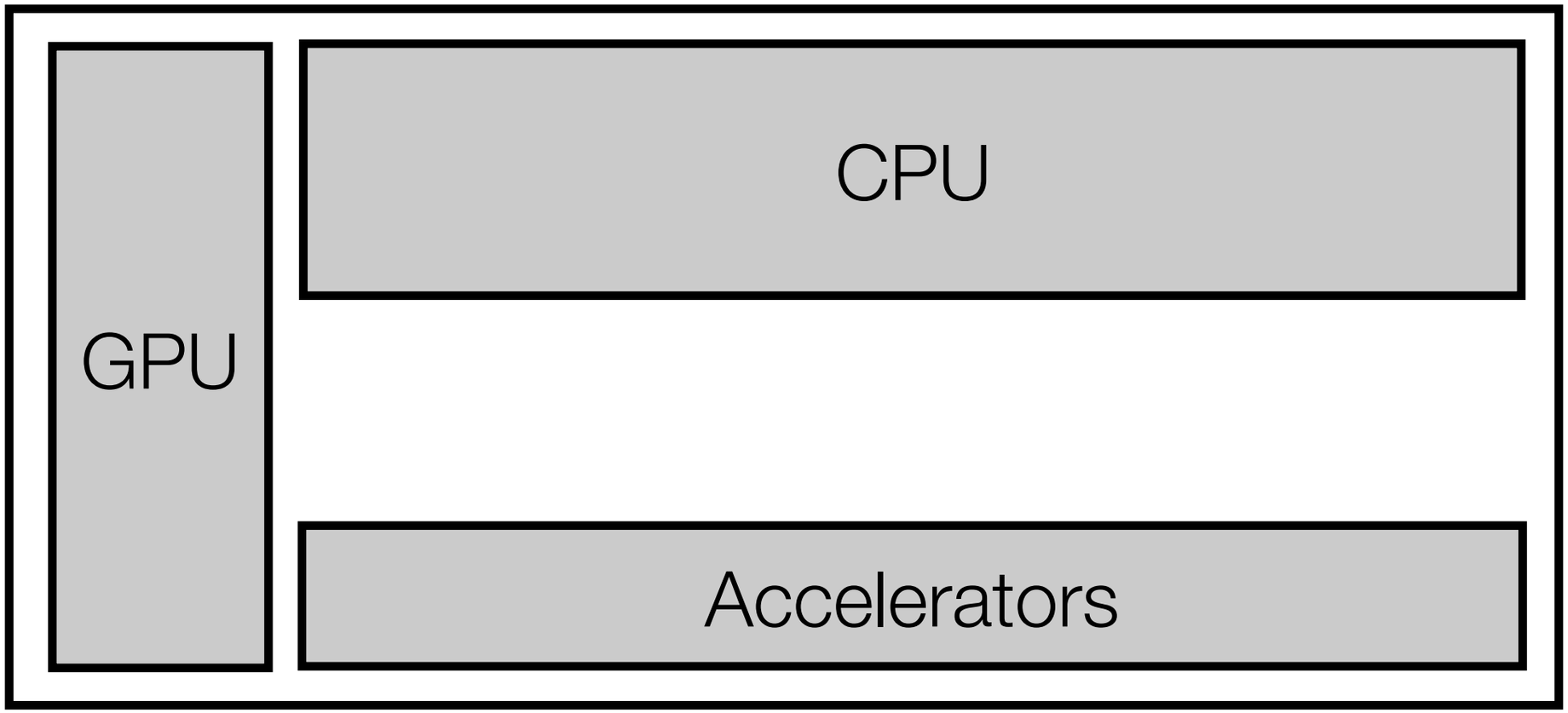

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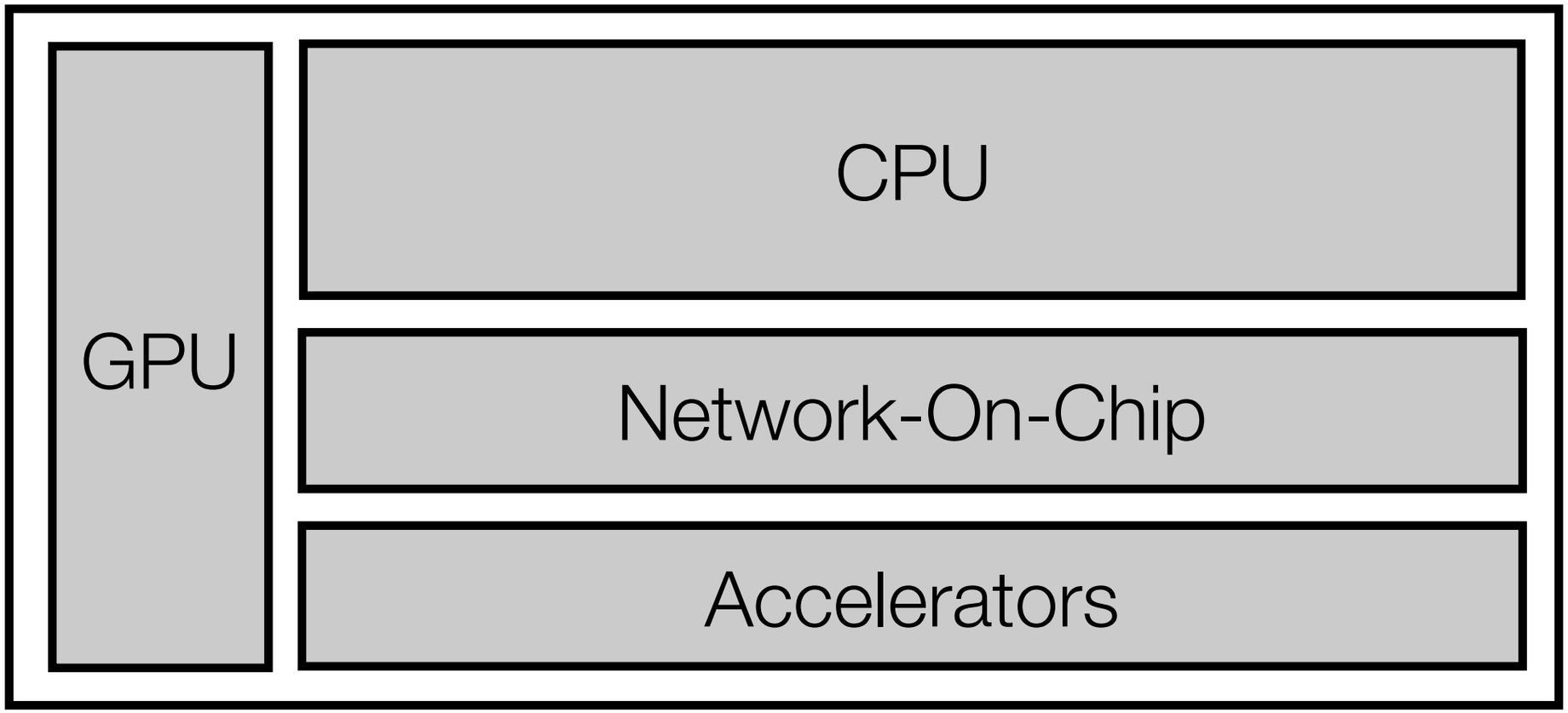
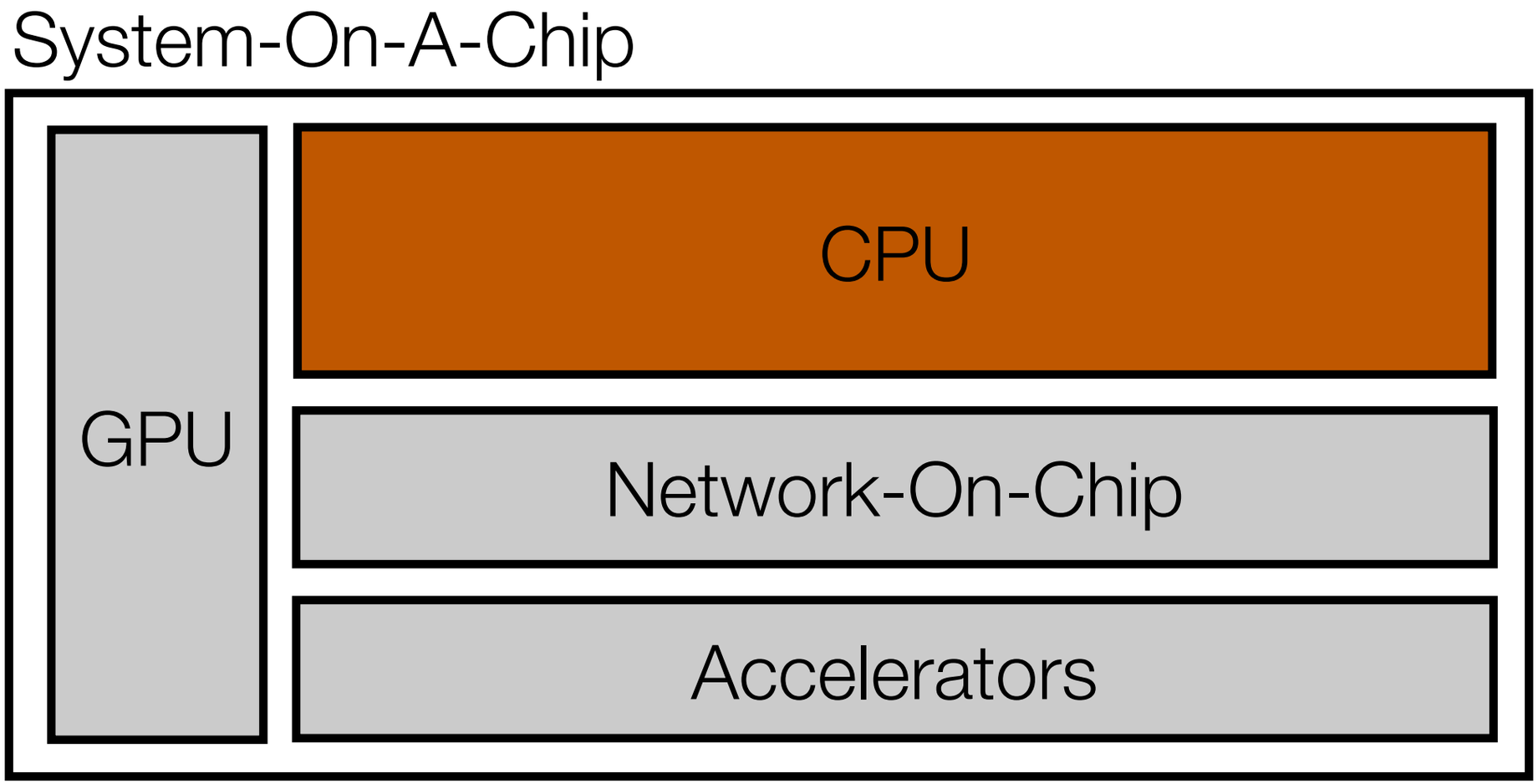
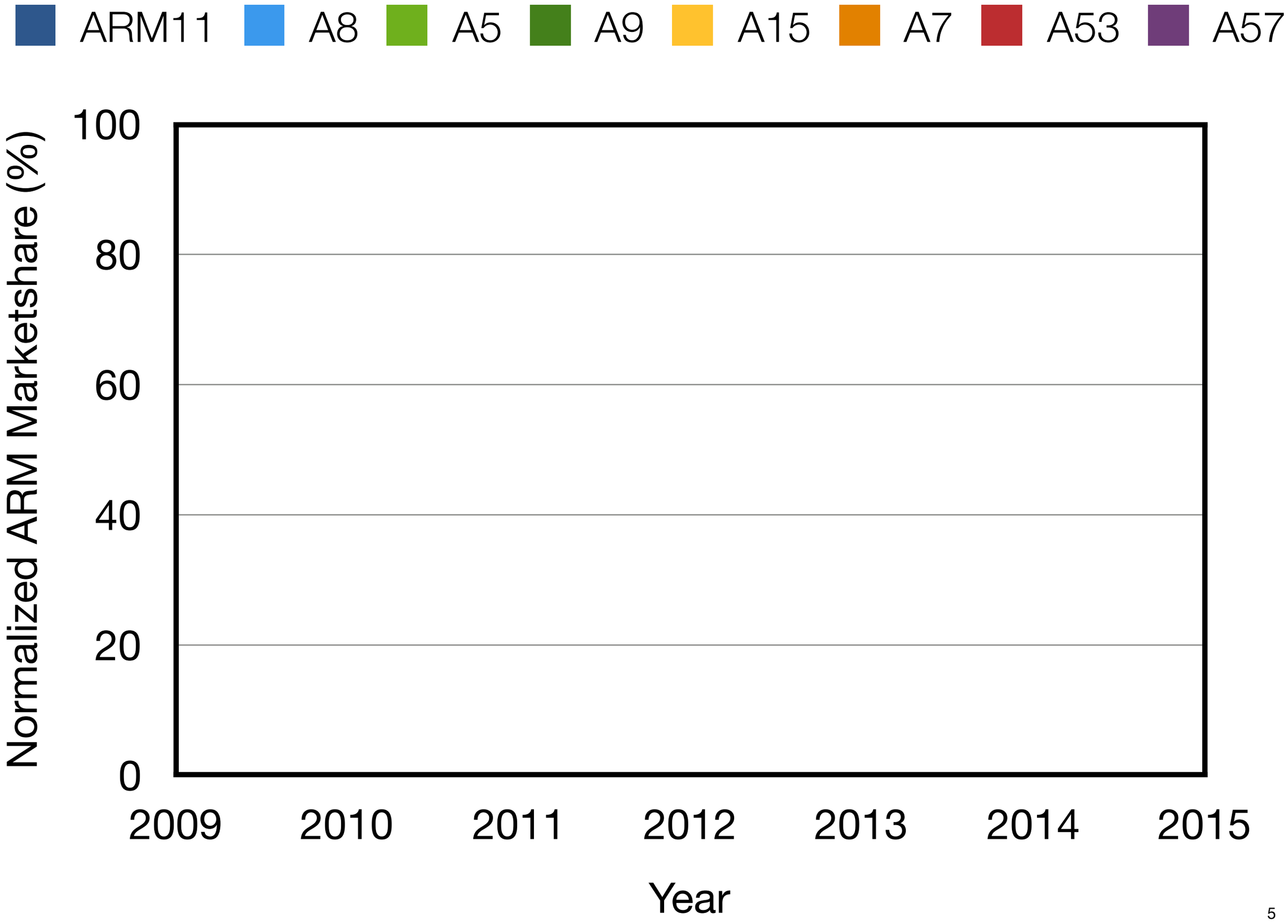
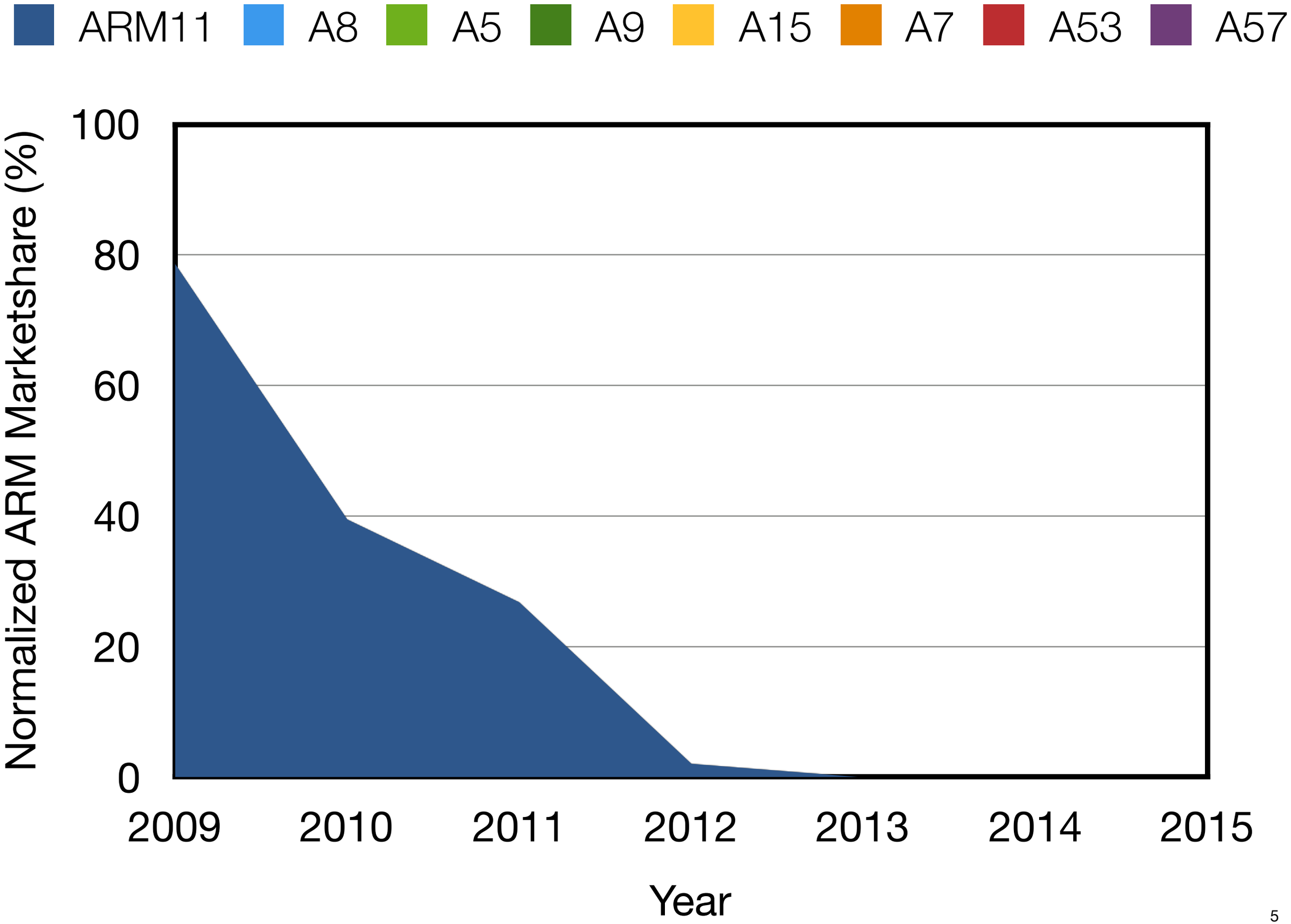



System-On-A-Chip
CPU
GPU
Network-On-Chip
Accelerators


ARM11
A8
A5
A9
A15
A7
A53
A57
Normalized ARM Marketshare (%)
100
80
60
40
20
0
2009
2010
2011
2012
2013
2014
2015
Year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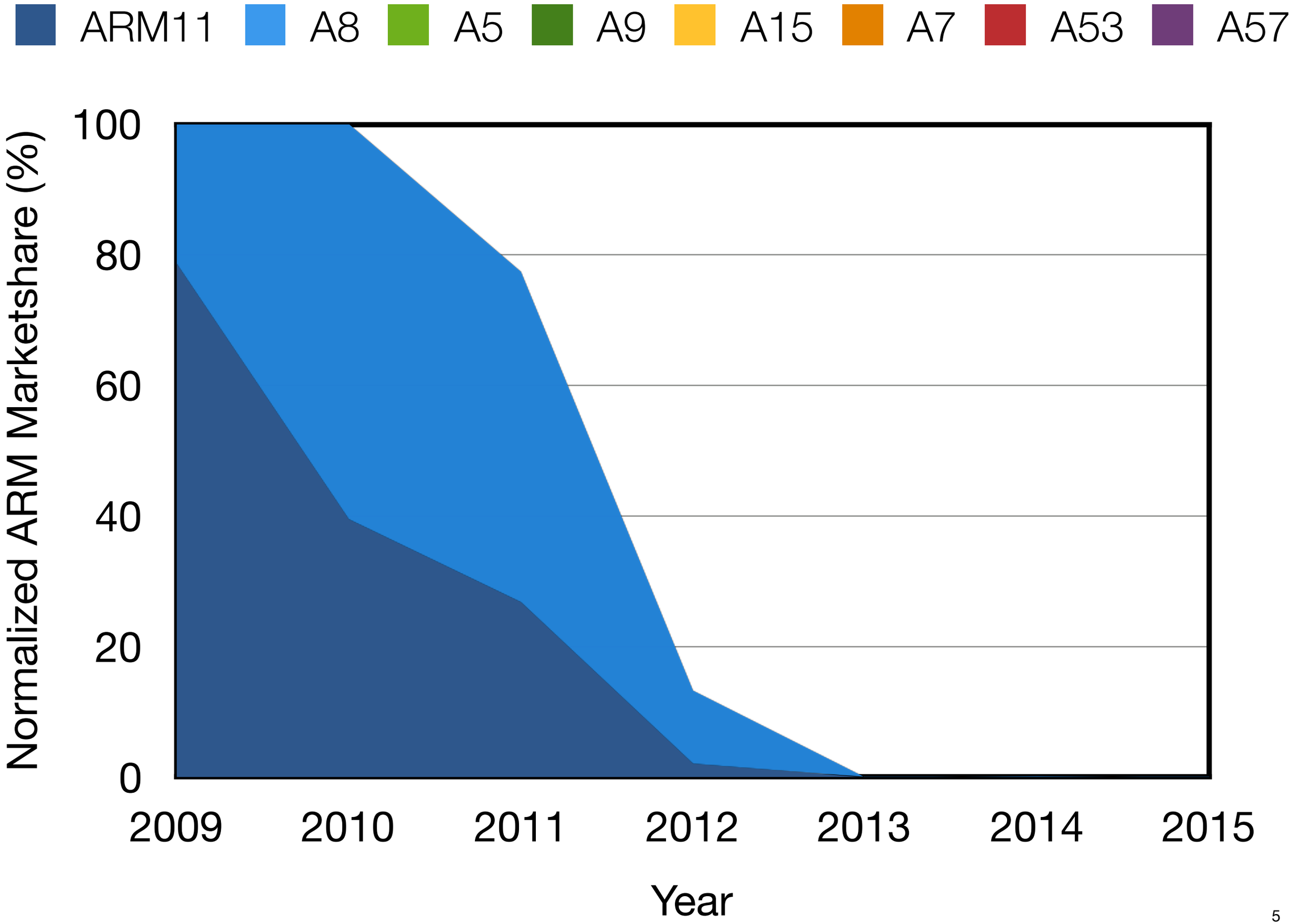
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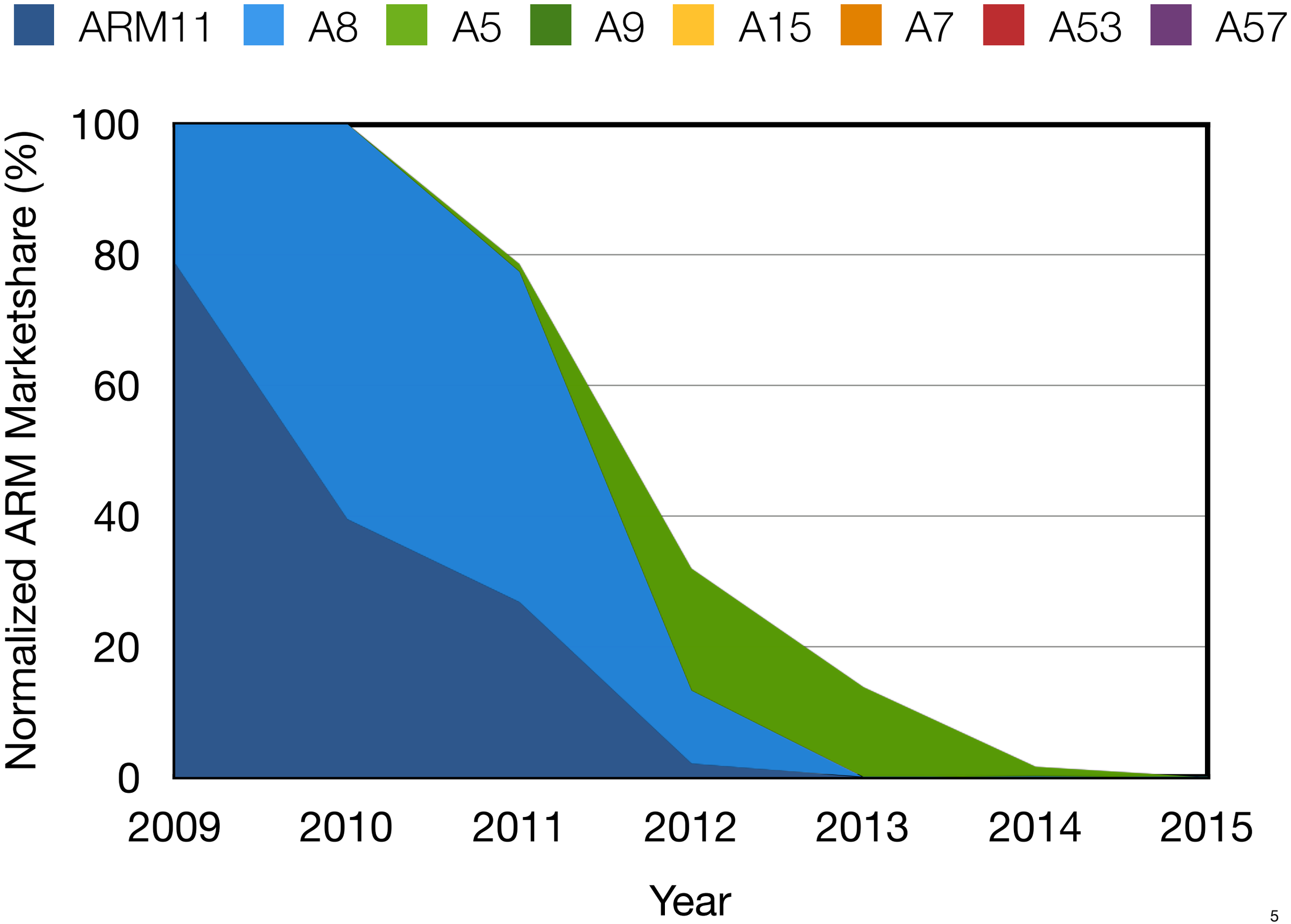
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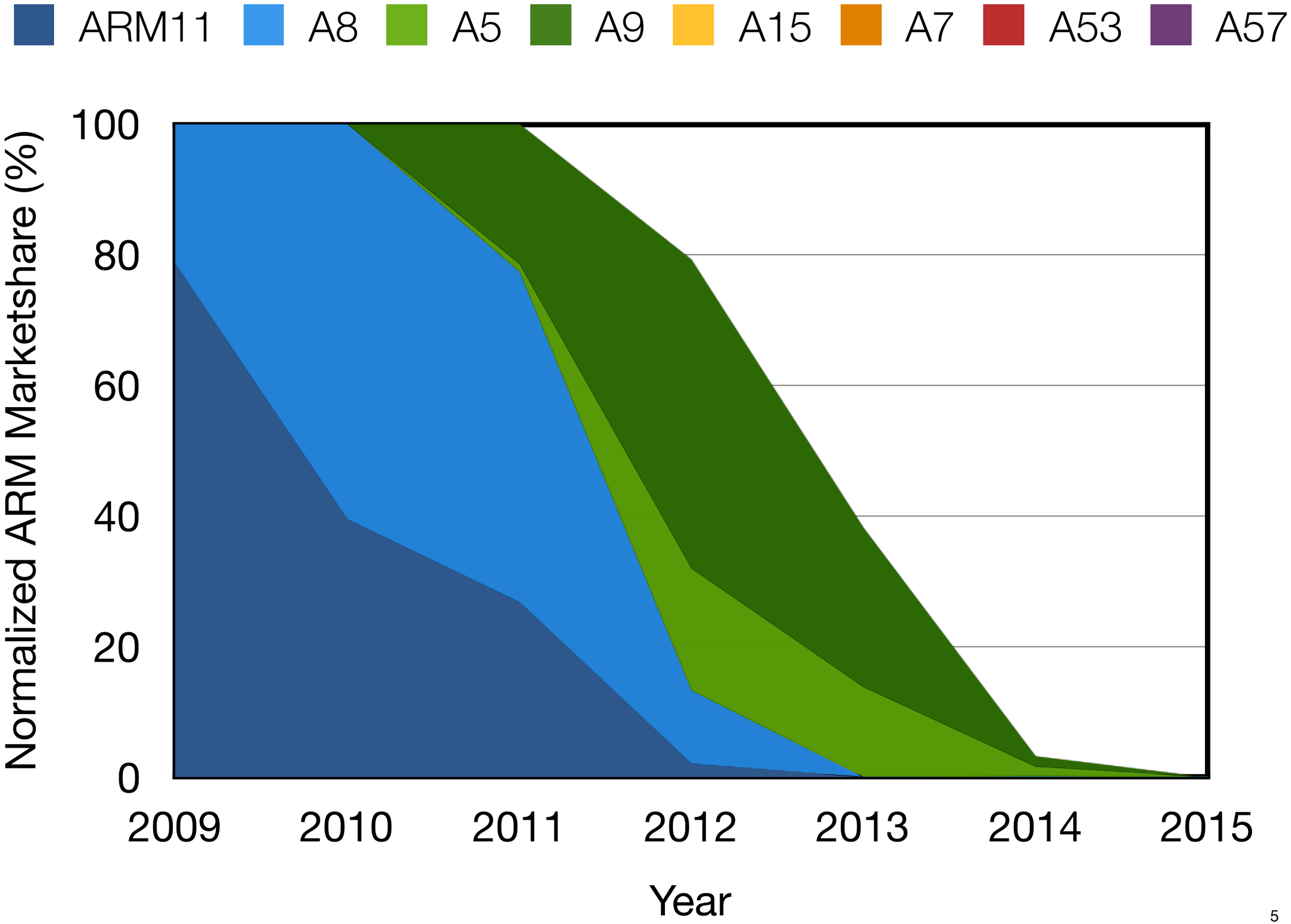
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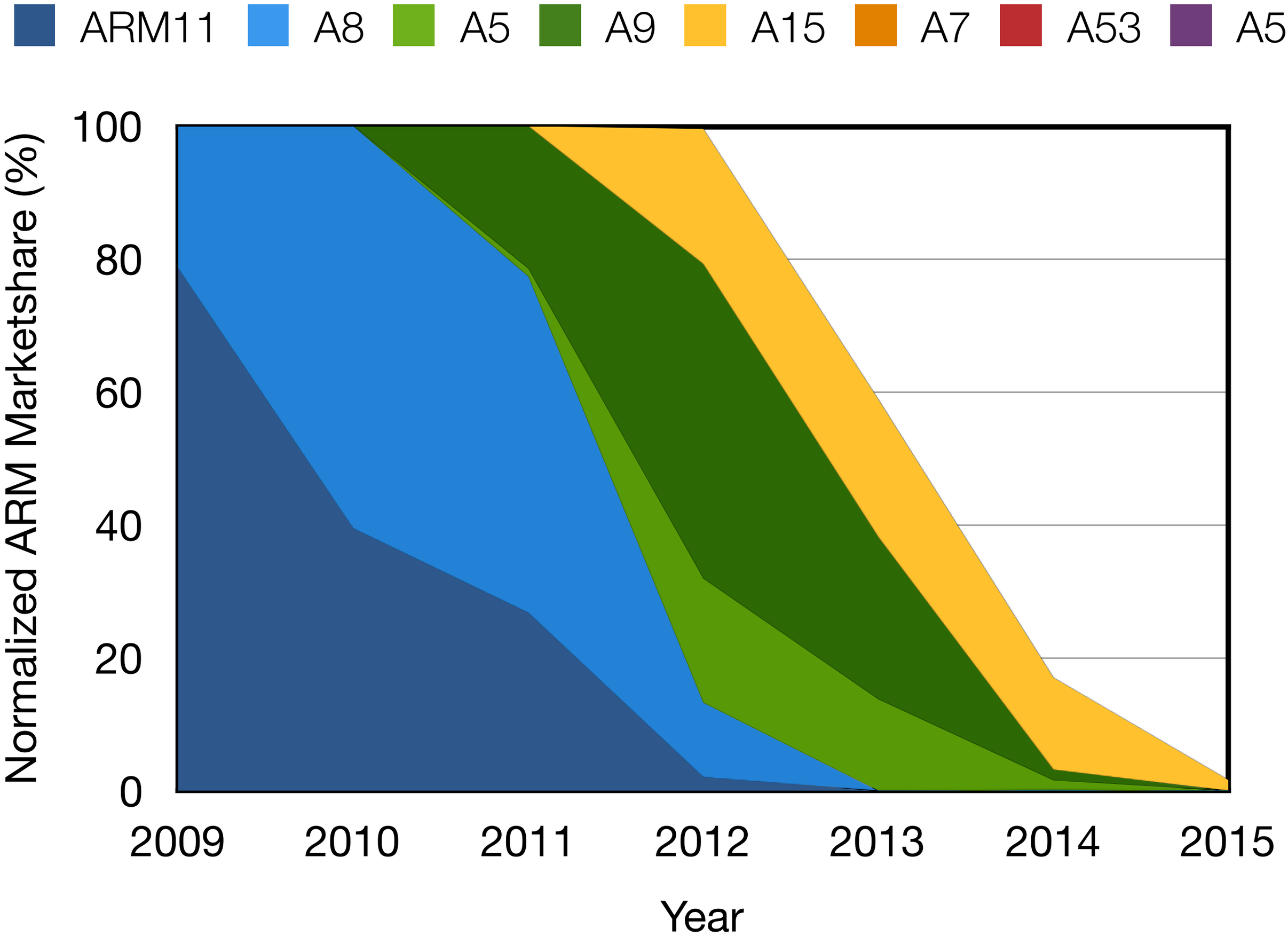
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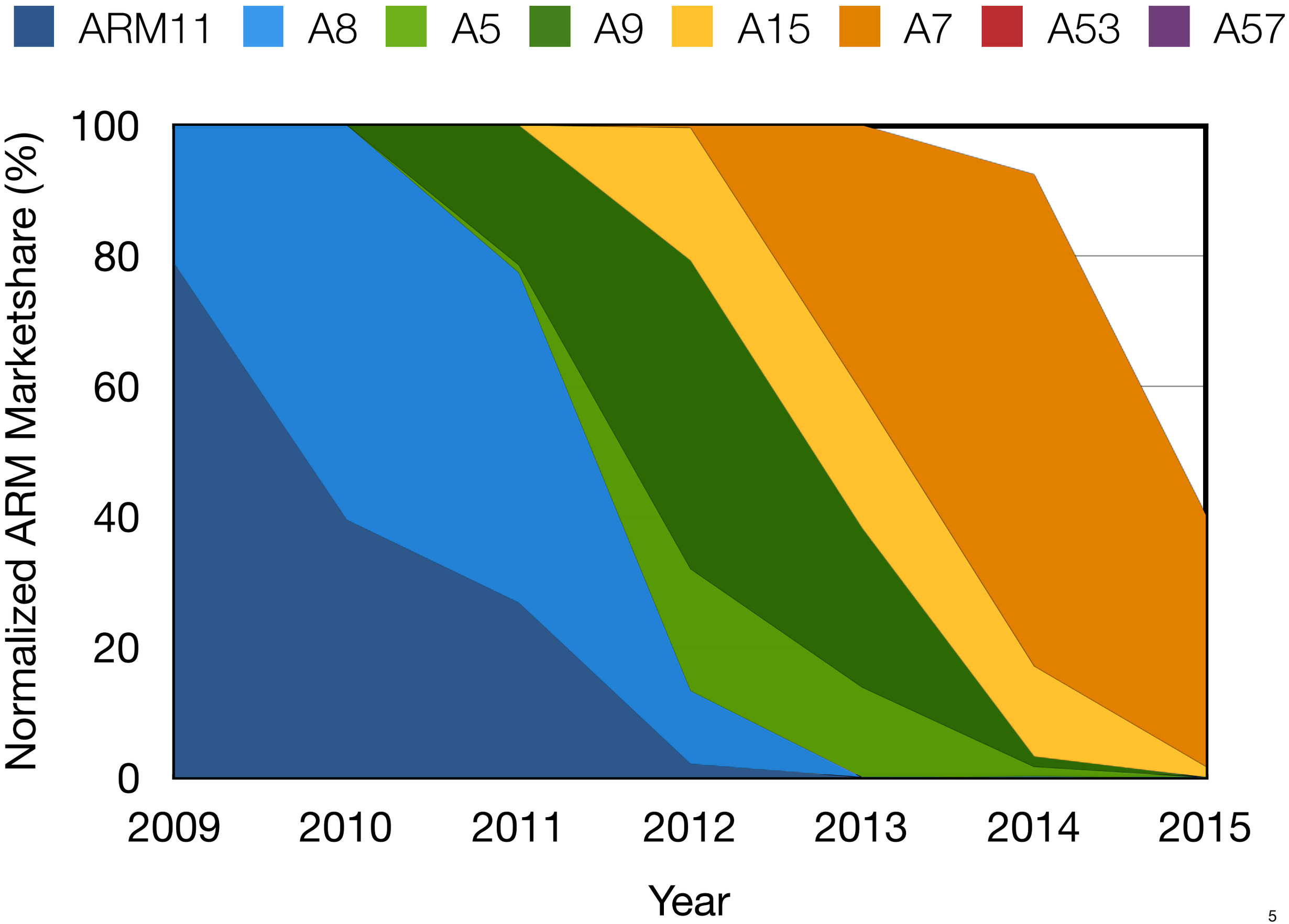
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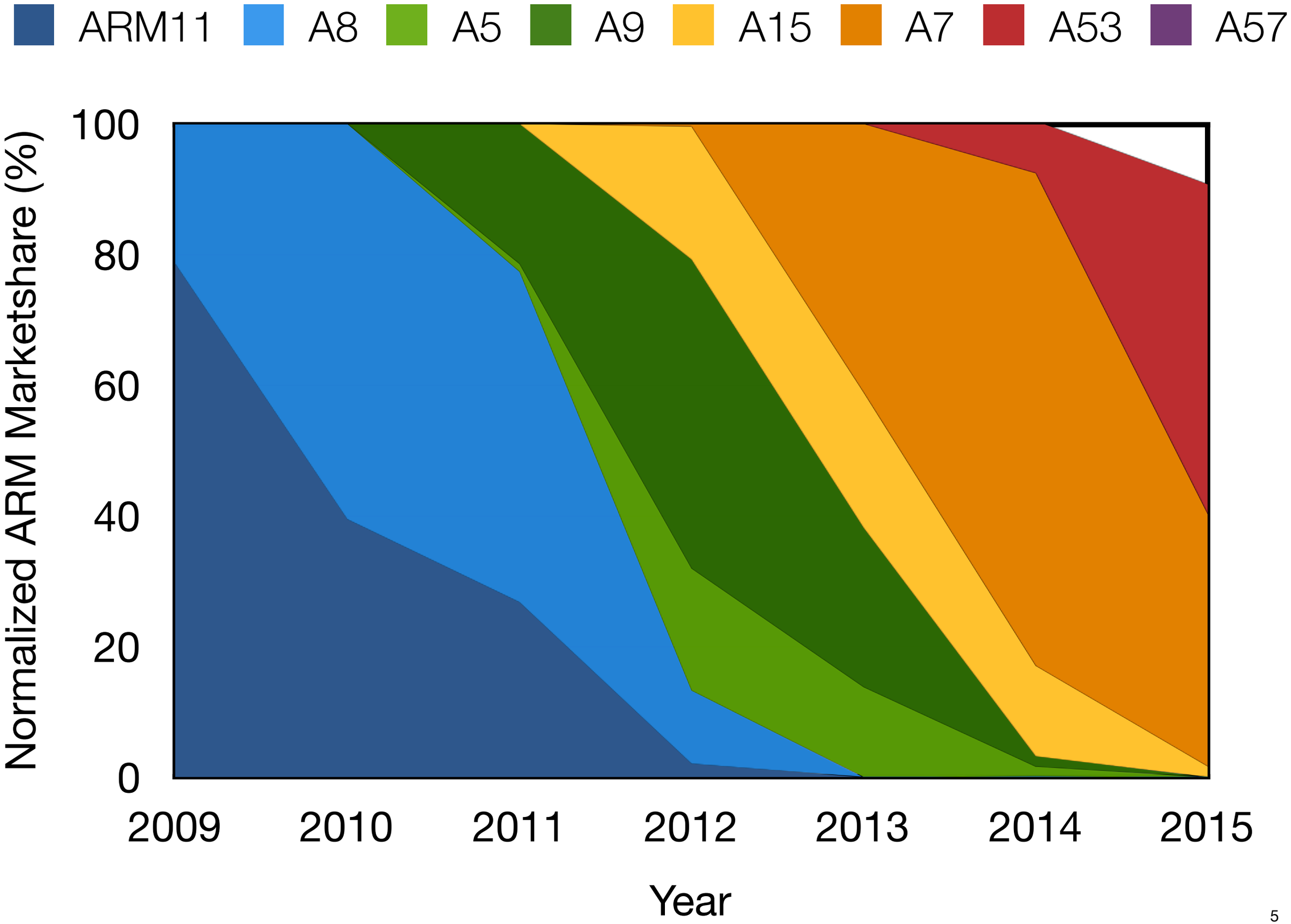
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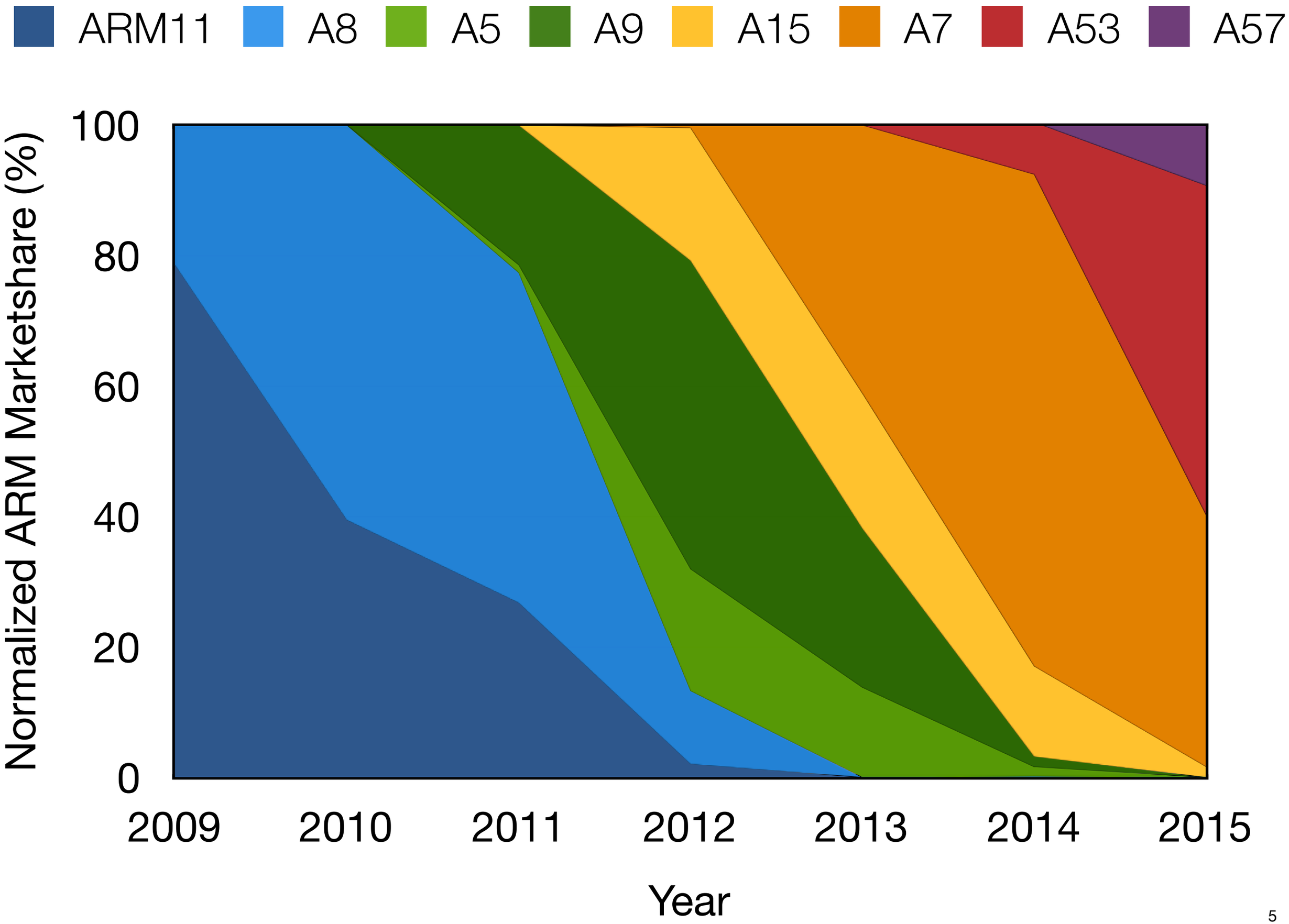
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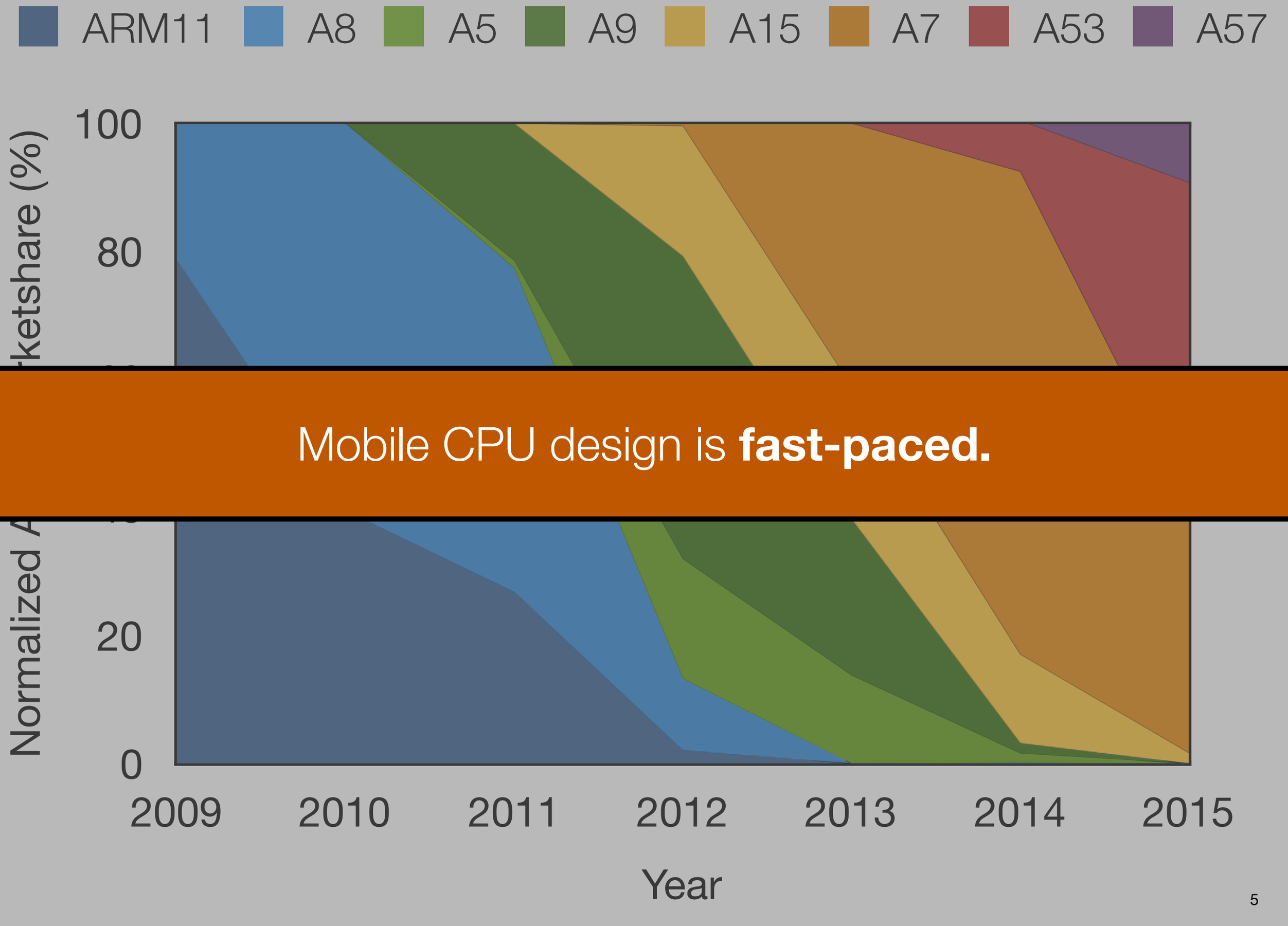


Mobile CPU design is **fast-paced.**

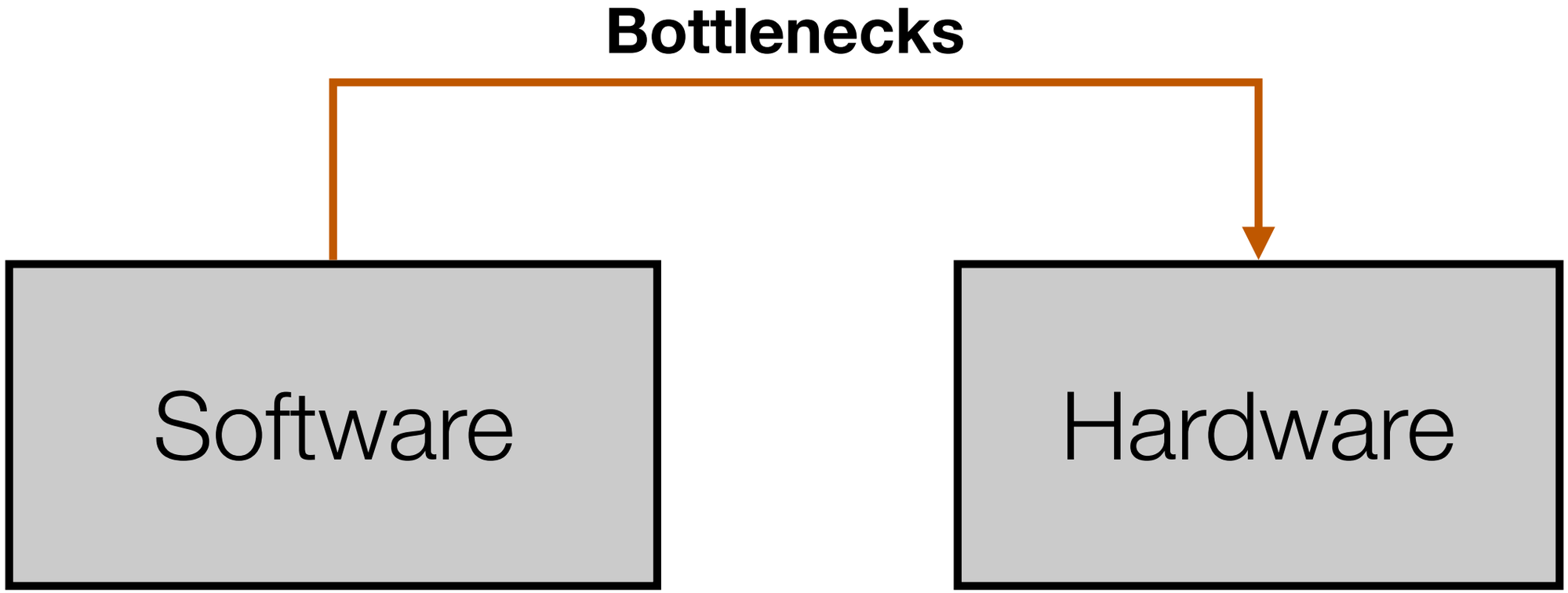
Conventional Research Scope

Conventional Research Scope

Software

Hardware

Conventional Research Scope



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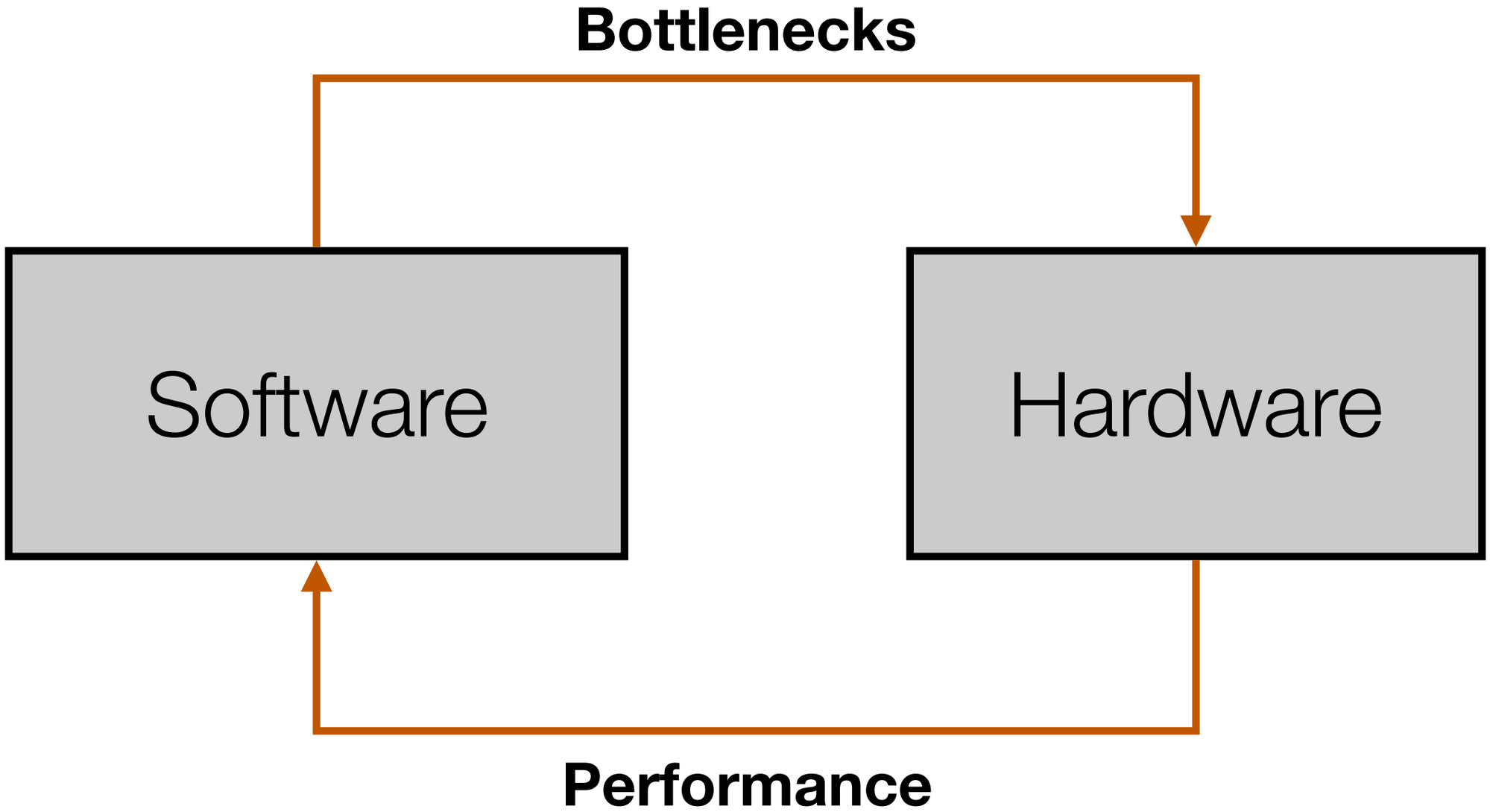

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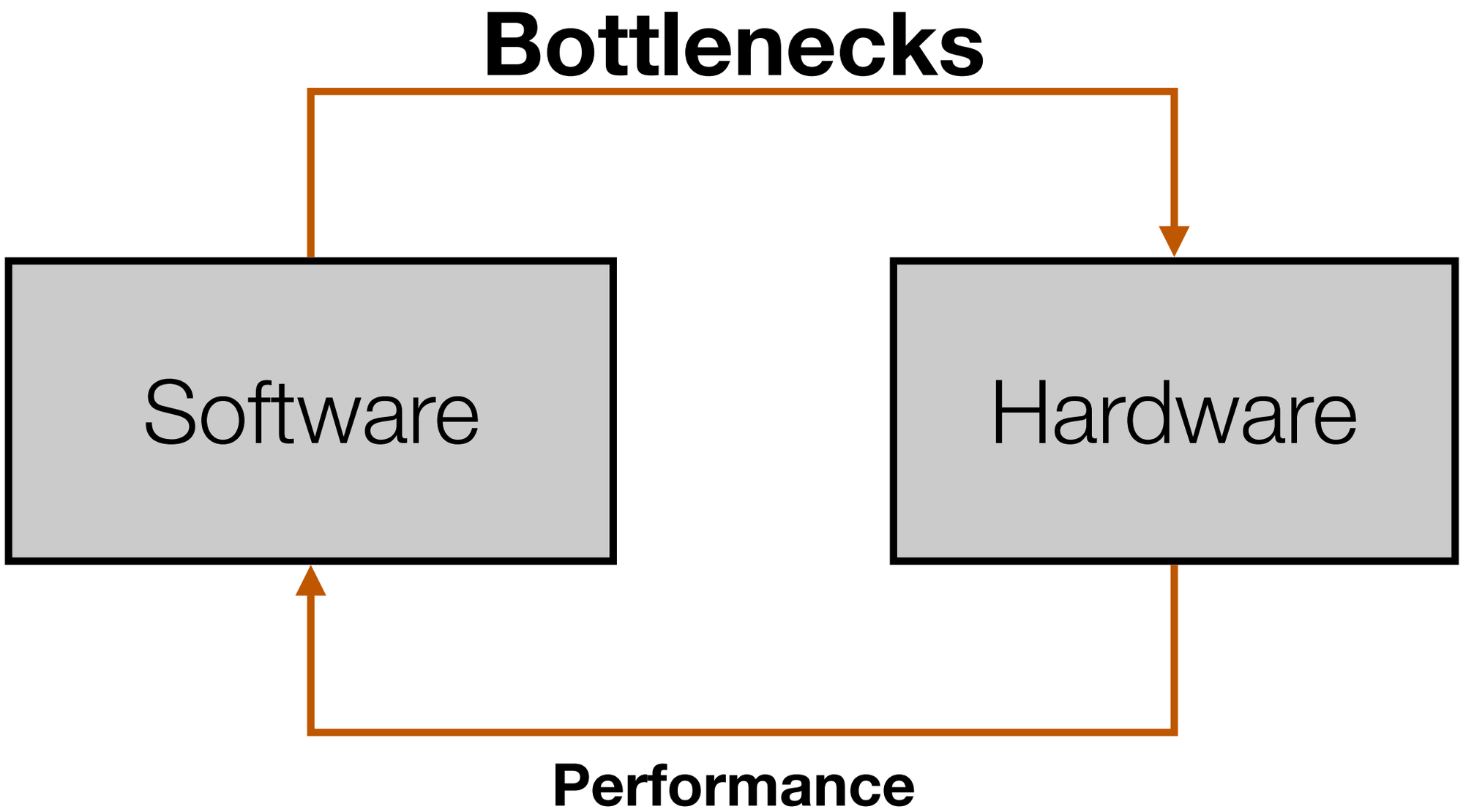

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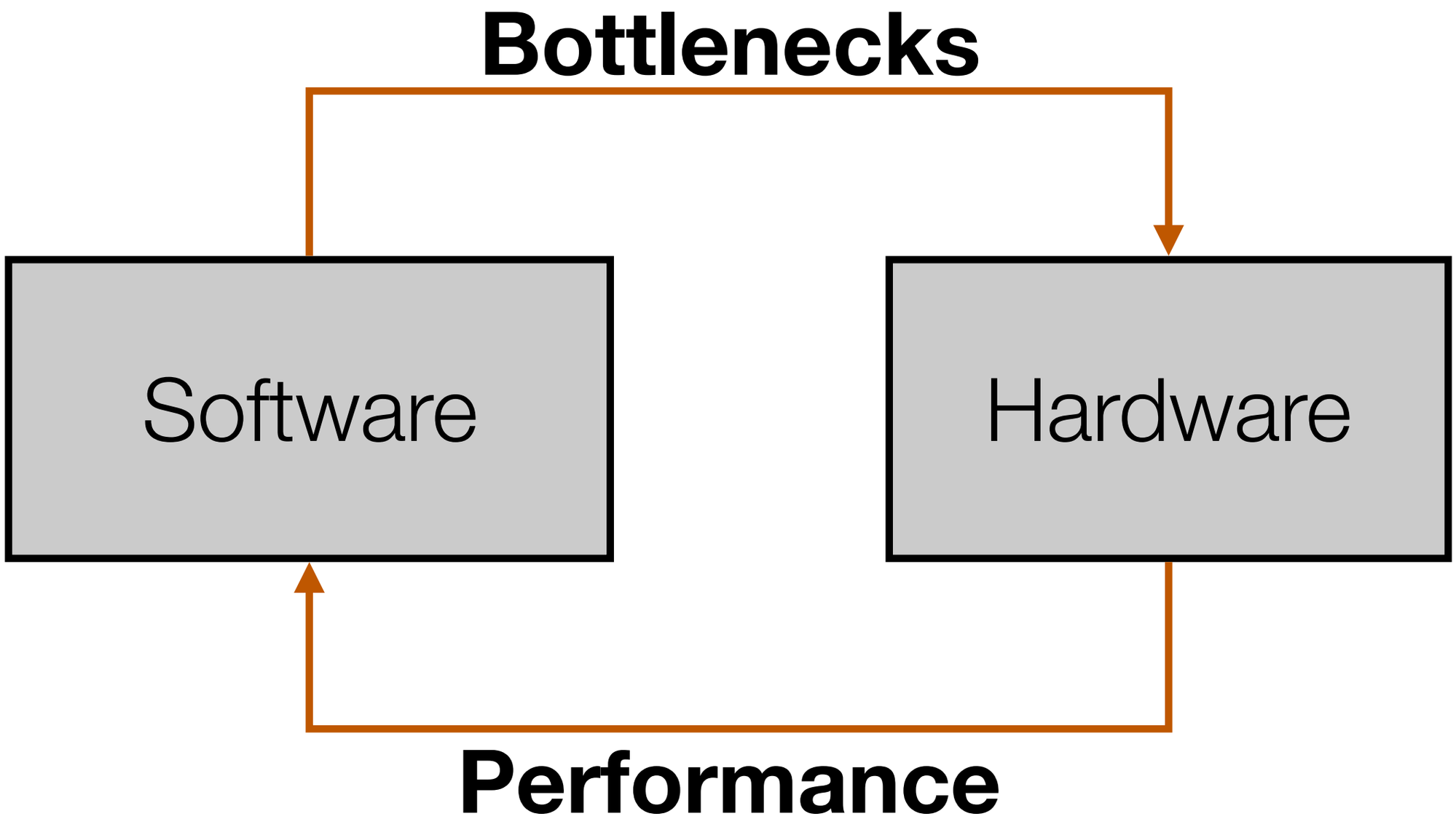
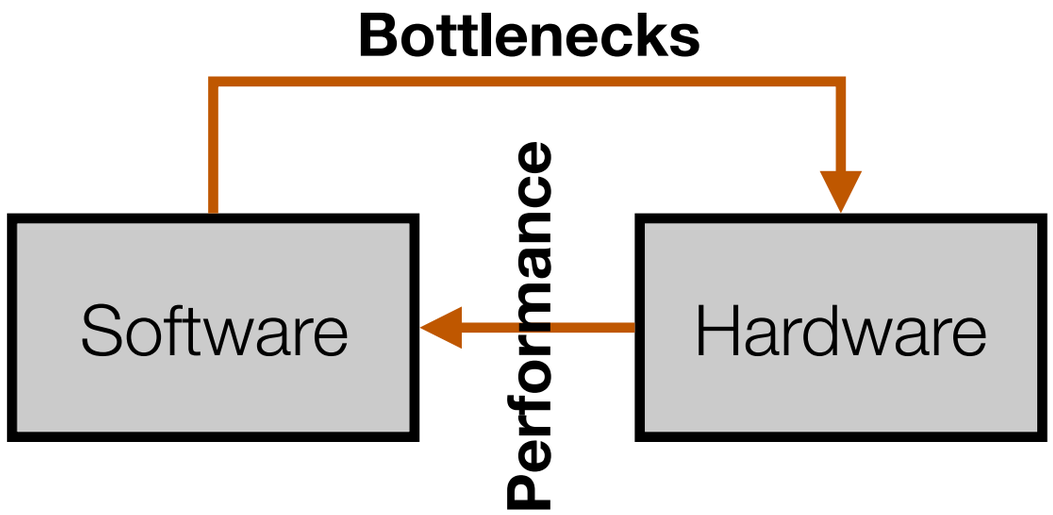


Expanding the Research Scope



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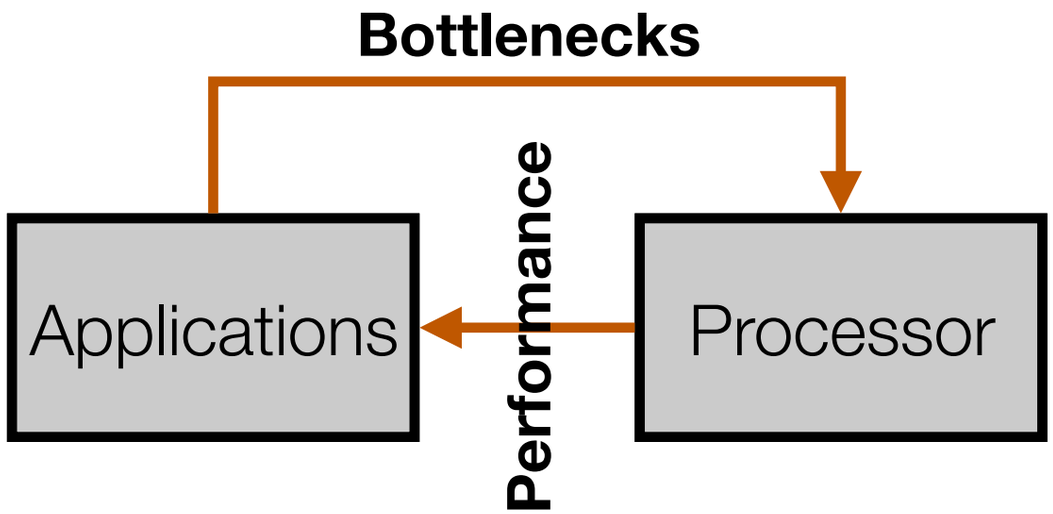

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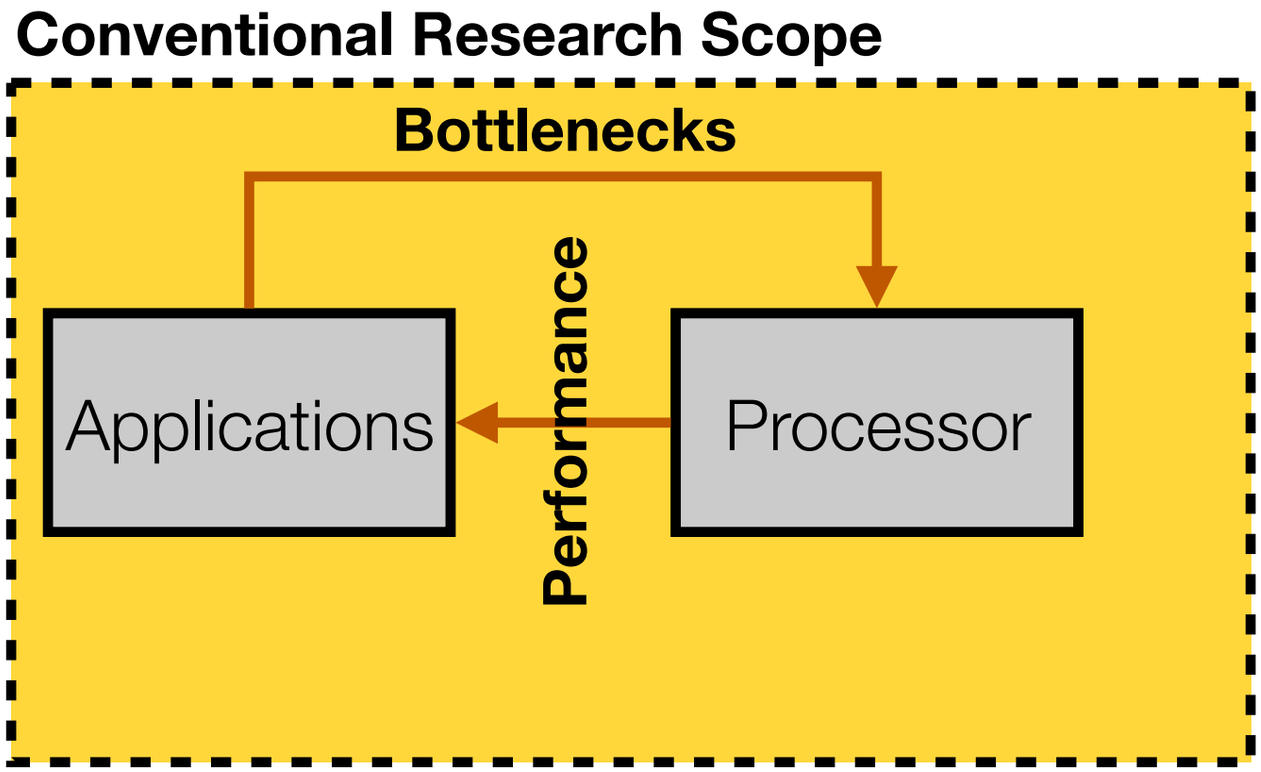

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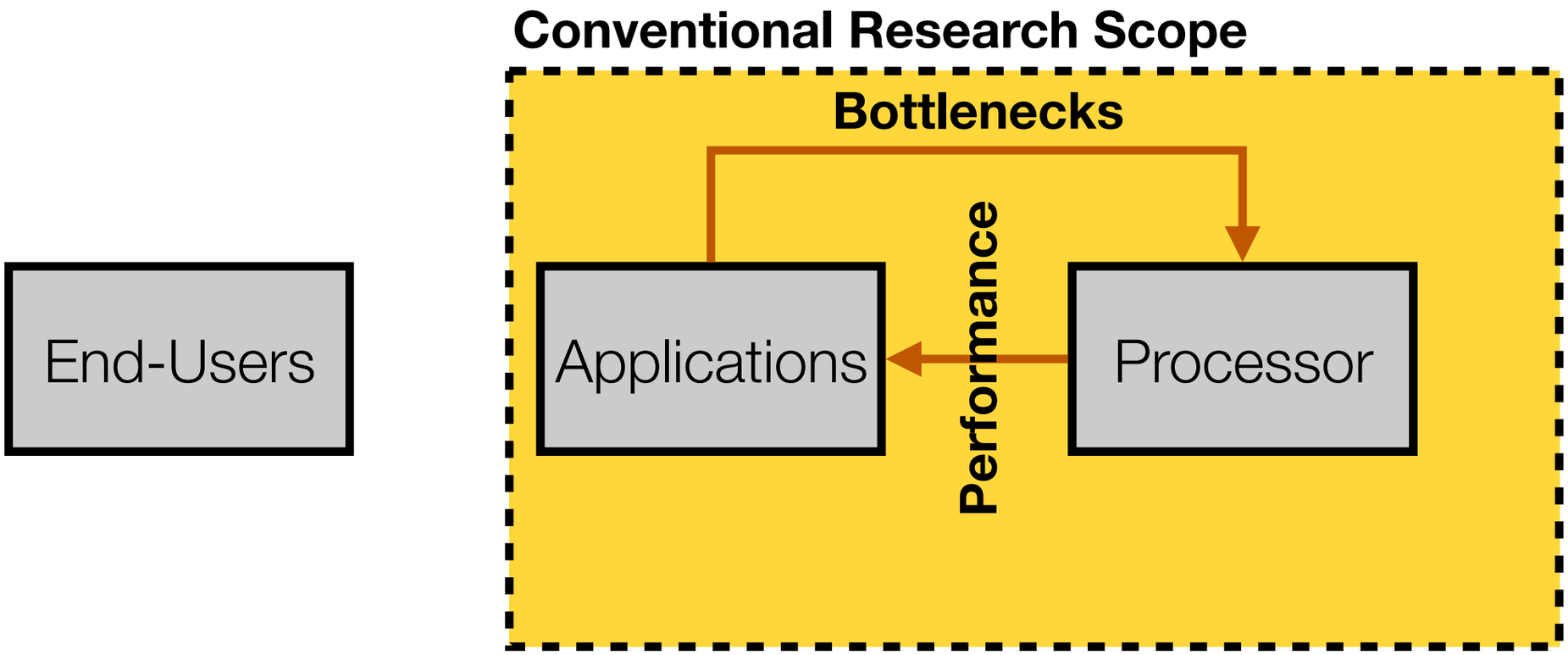

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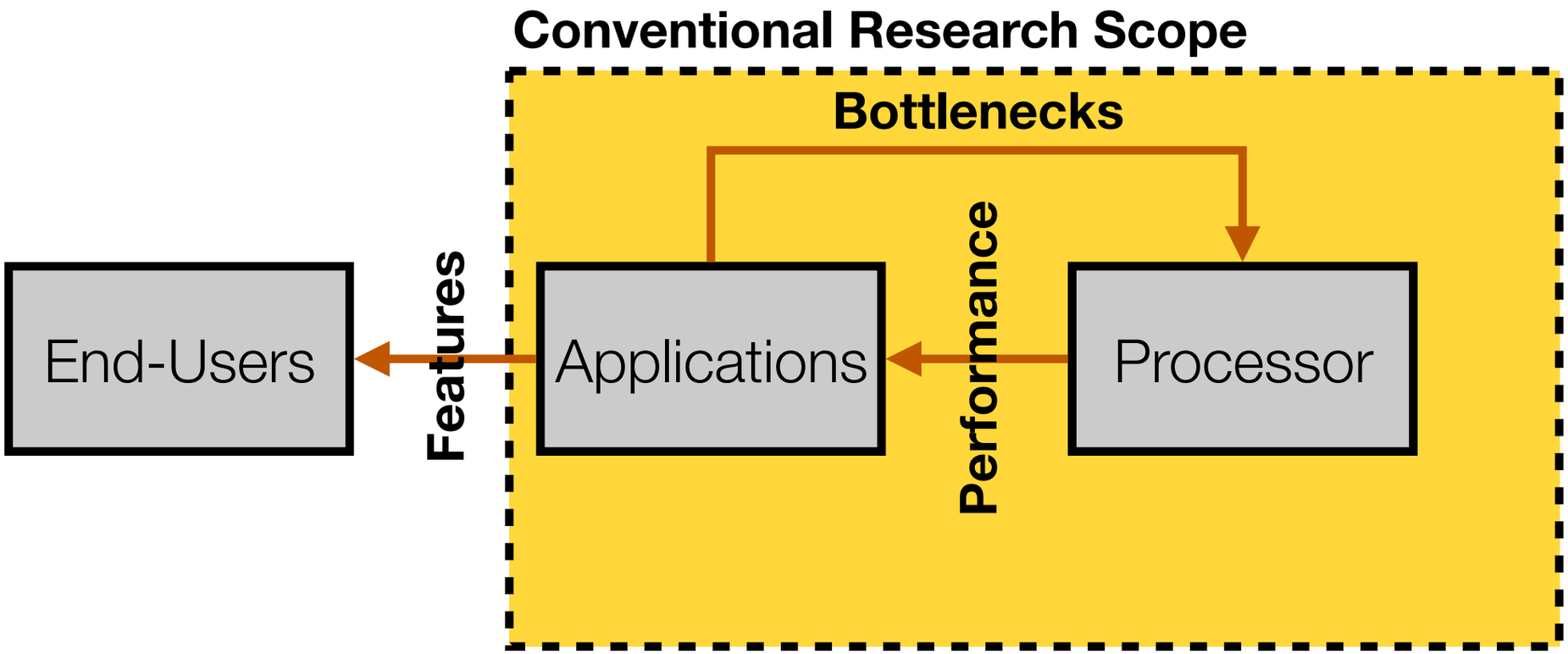

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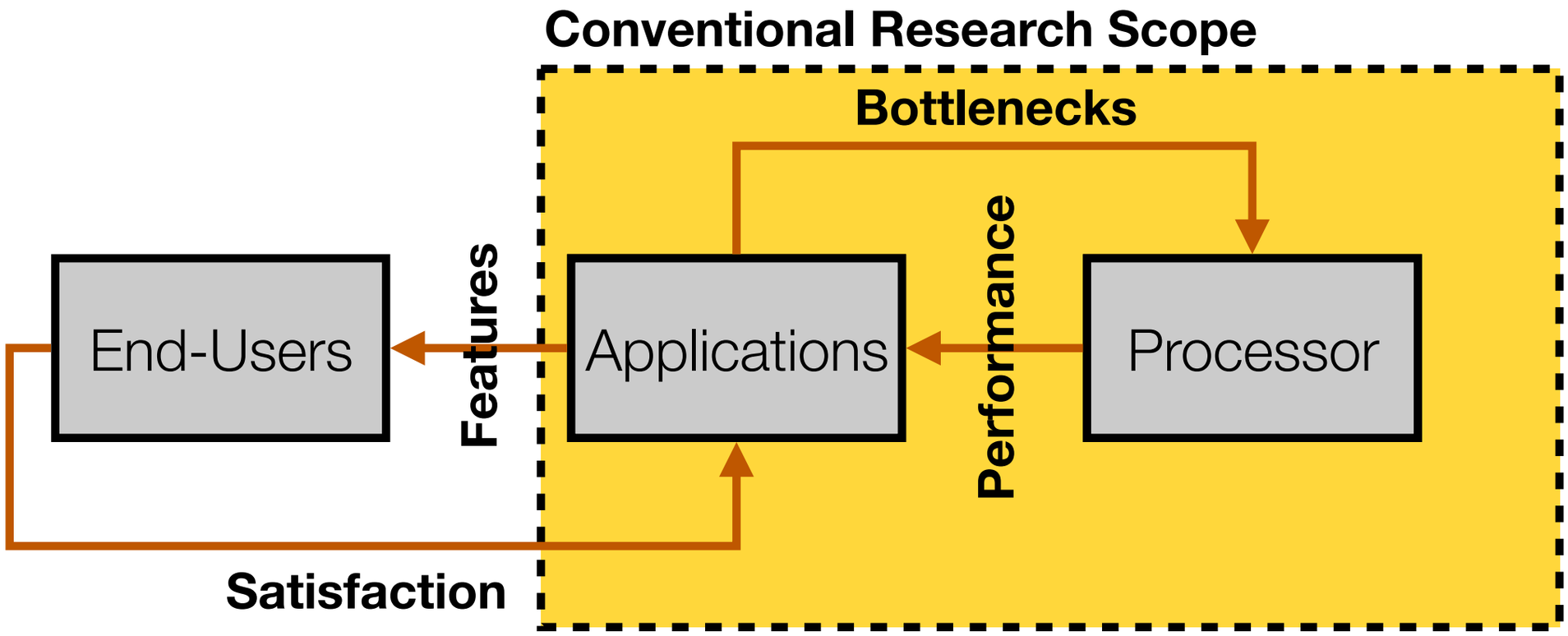

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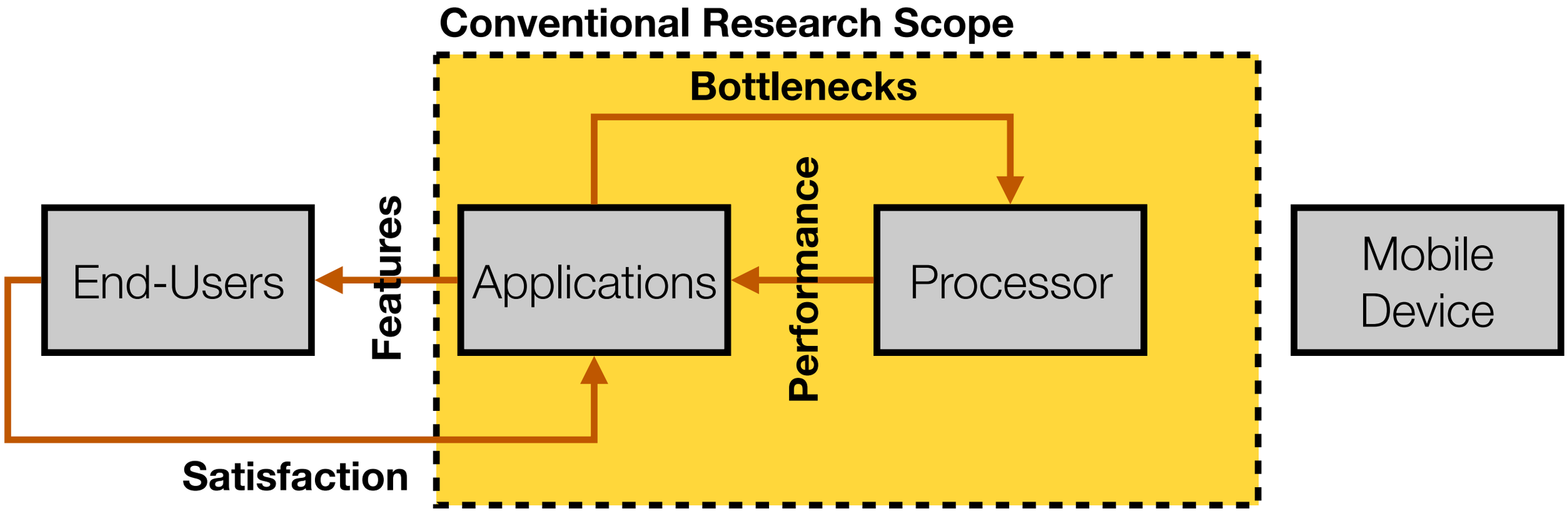

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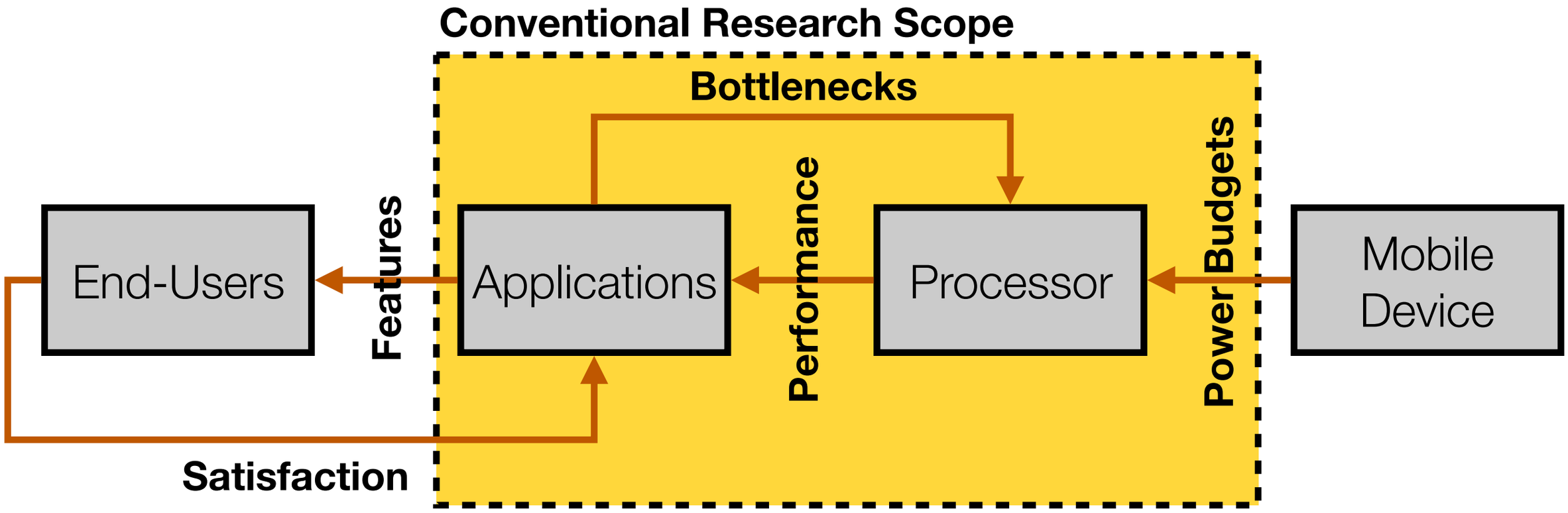

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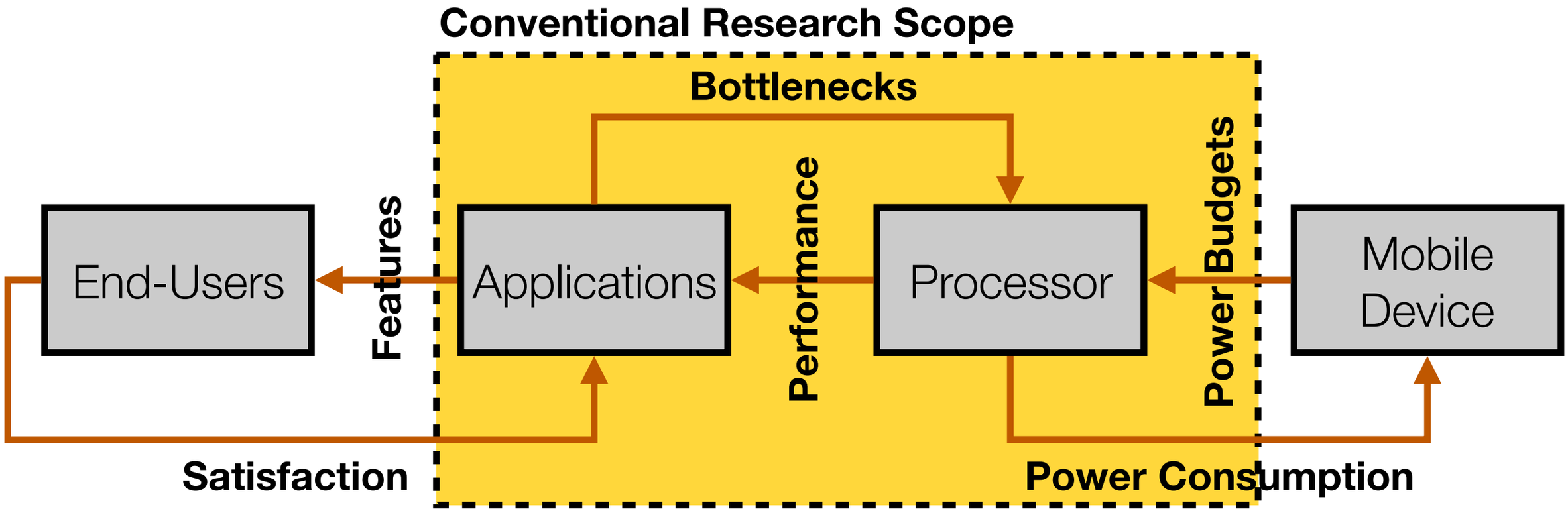

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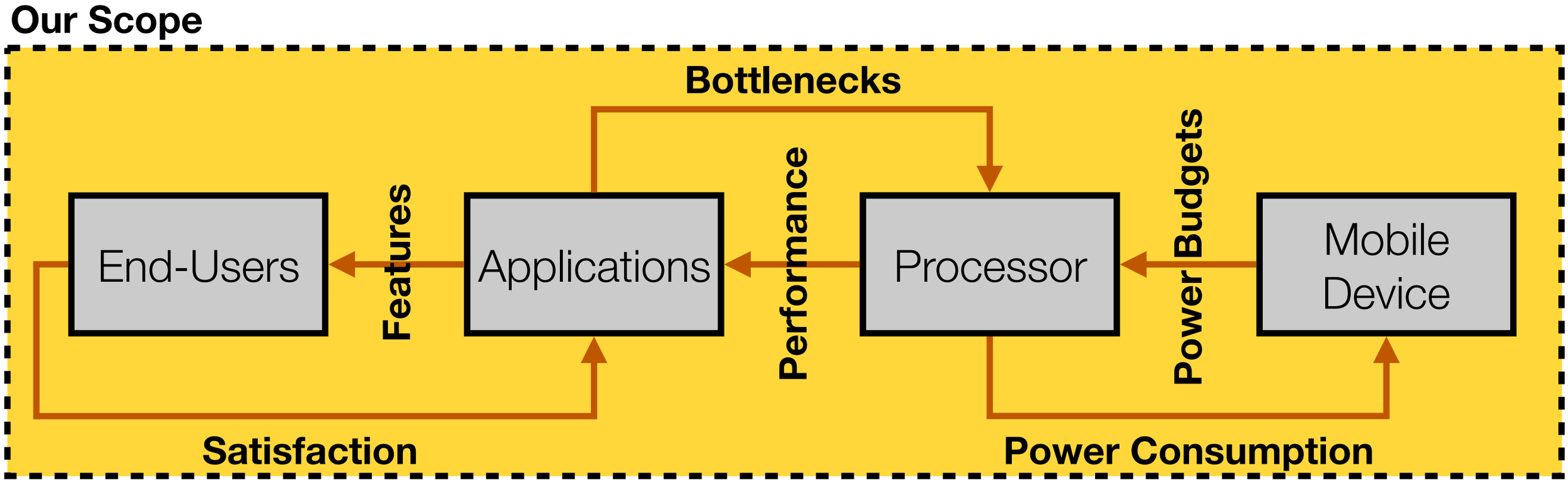

Characterize how the **interactions** between mobile CPU, end-user, and mobile device have **changed over time** through **real-world measurement**

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1. Has mobile CPU efficiency improved?
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3. How has the rest of the mobile device evolved around the CPU?

real-world measurement

real-world measurement

Capturing Real-world Mobile CPU Trends from Off-the-Shelf Smartphones

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L1 I$	32 KB	32 KB	32 KB	32 KB	32 KB	32 KB	48 KB
L1 D$	32 KB	32 KB	32 KB	32 KB	32 KB	32 KB	32 KB
LLC	256 KB	512 KB	1 MB	2 MB	2 MB	2 MB	2 MB
DRAM	256 MB	512 MB	1 GB	1 GB	2 GB	2 GB	3 GB

Has mobile CPU efficiency improved?

Power

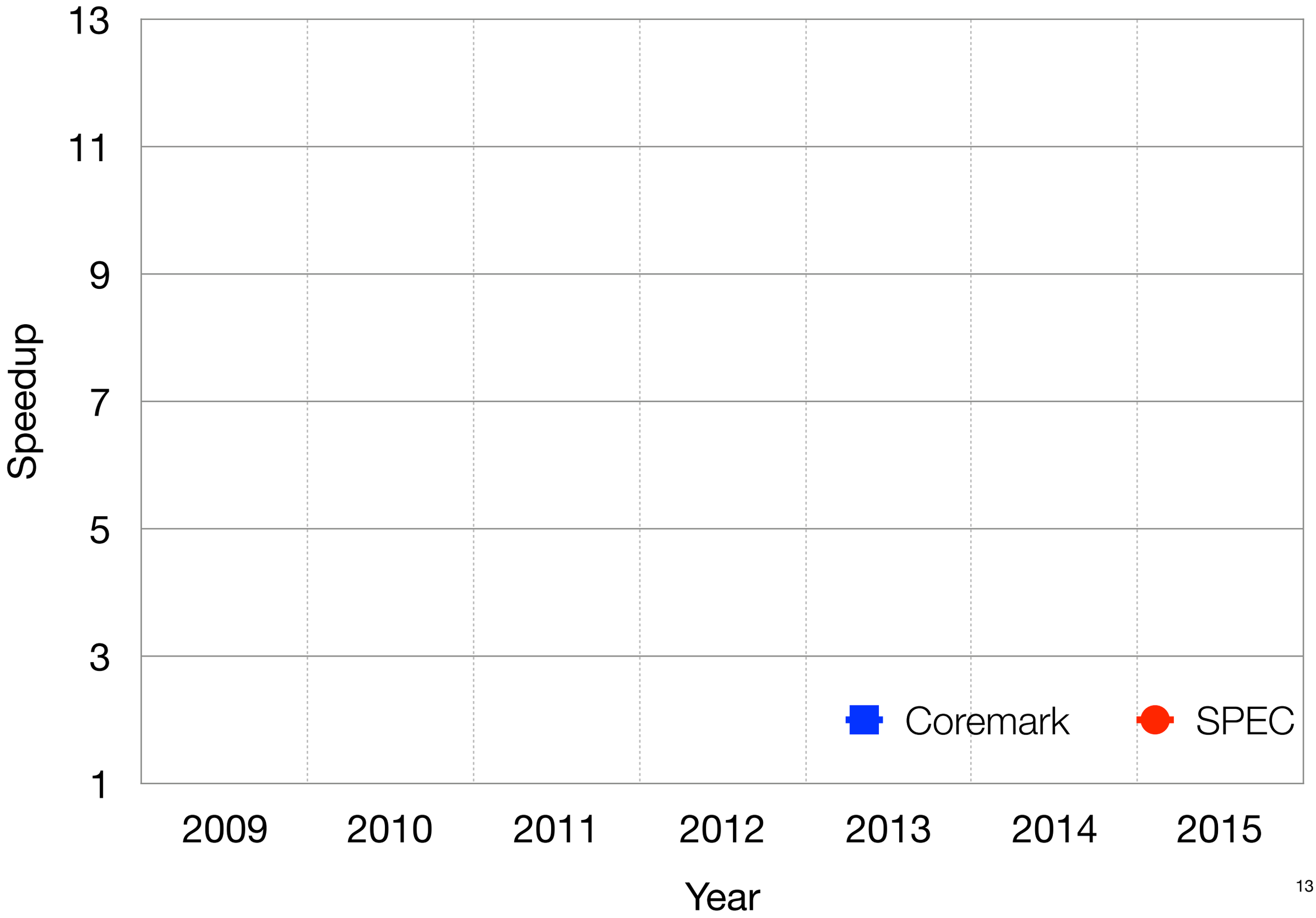
Has mobile CPU efficiency improved?

Performance

Energy

Substantial Performance Improvements

Substantial Performance Improvements



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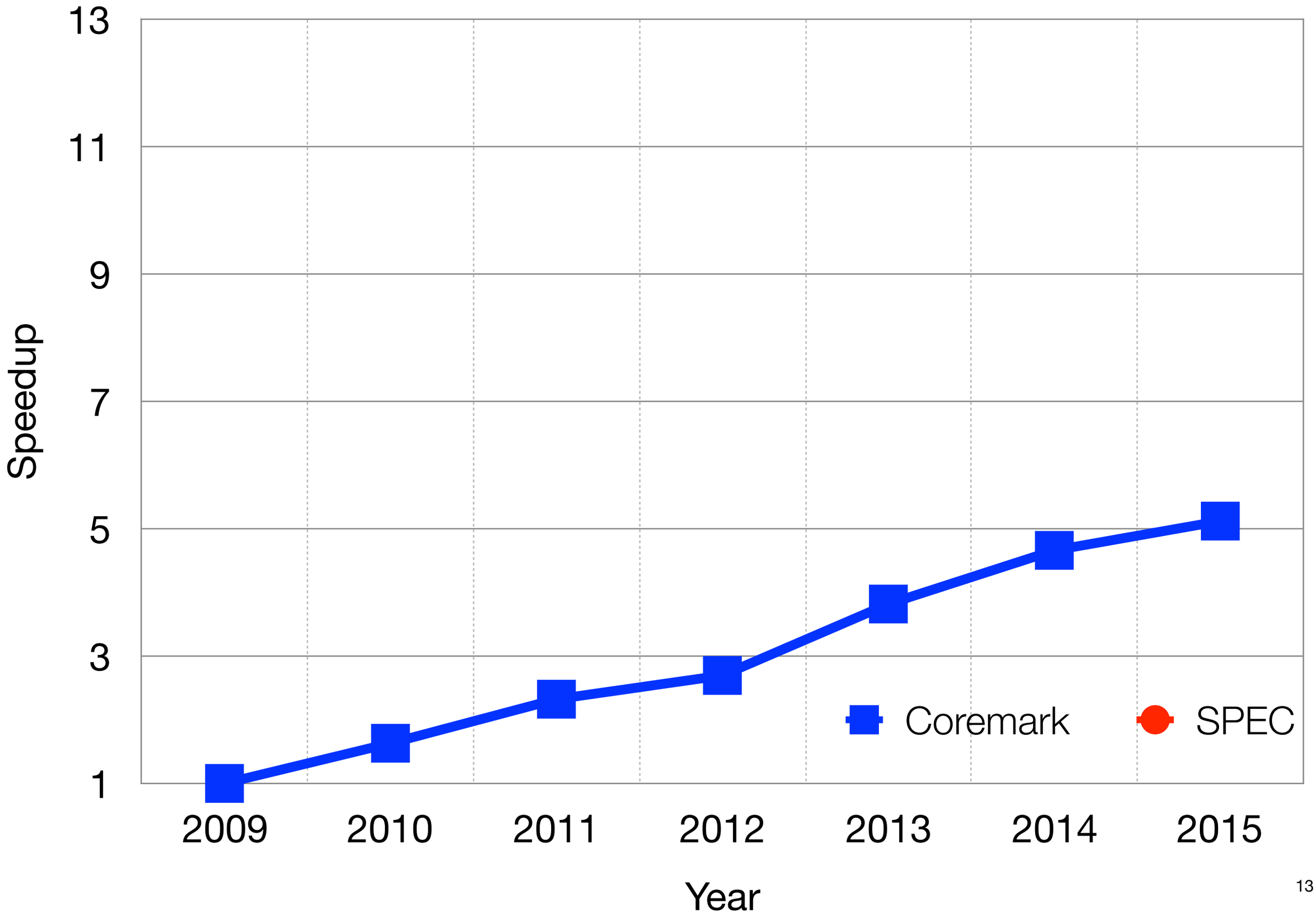

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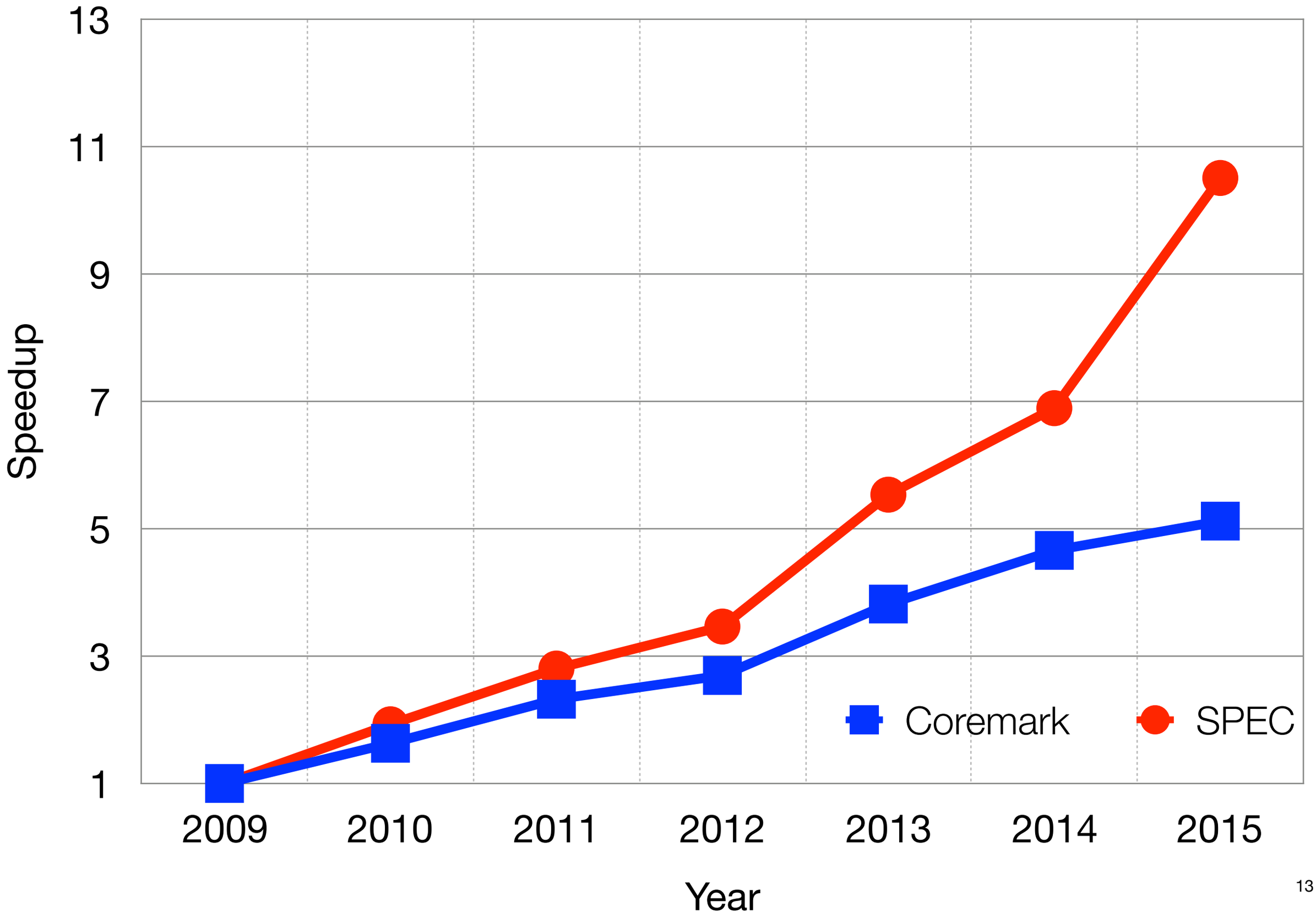

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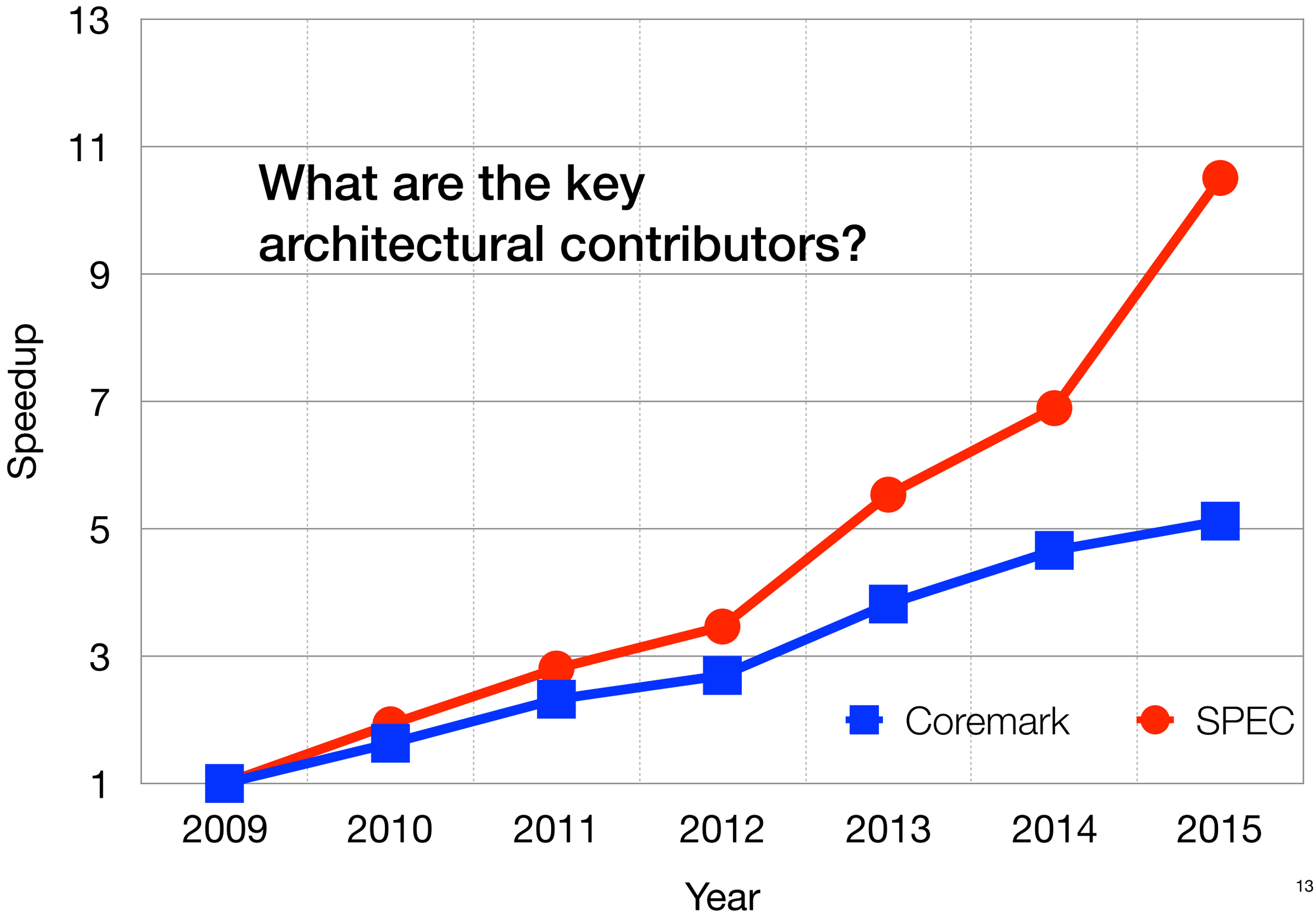

Speedup = IPC Speedup x Clock Speedup

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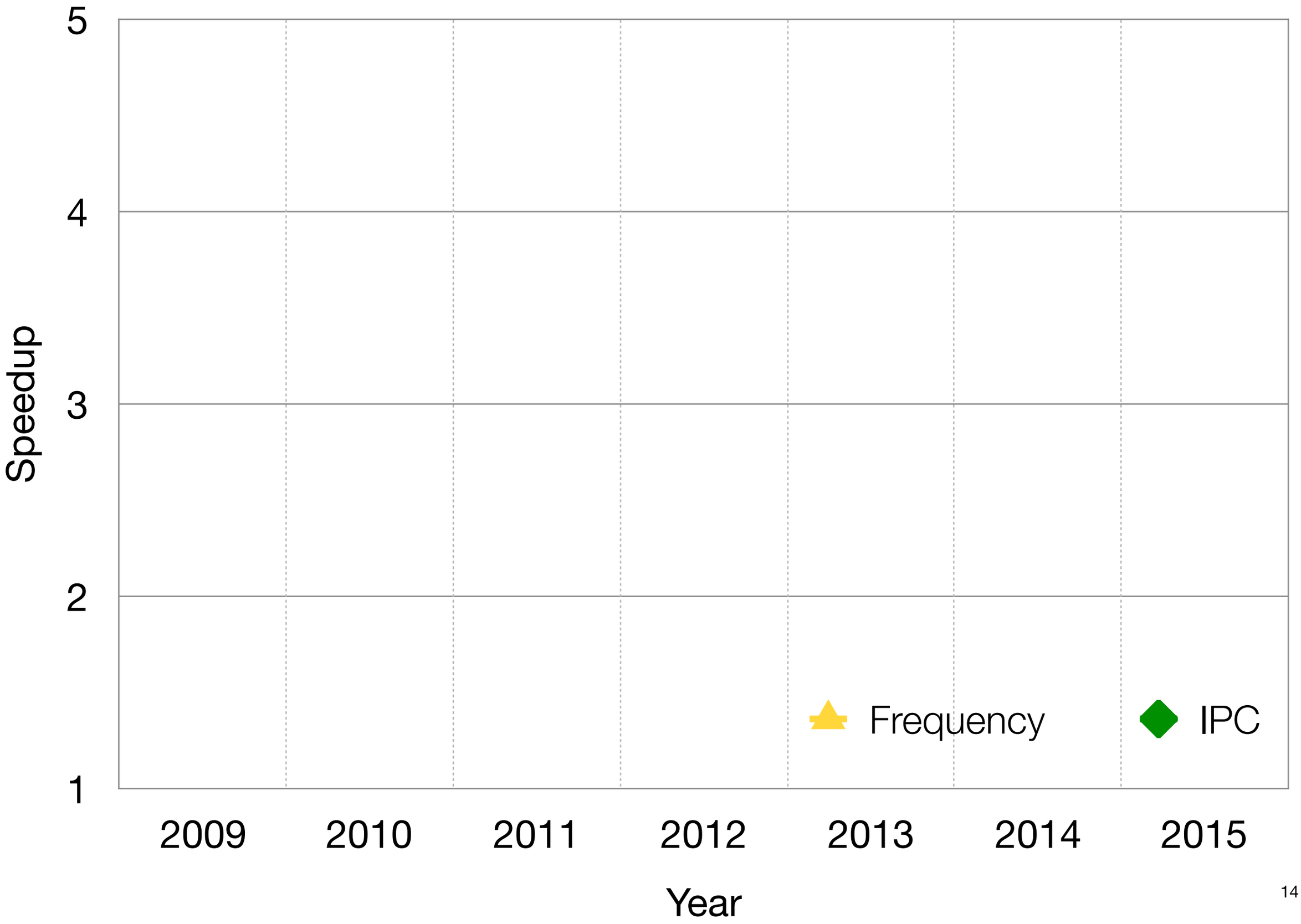

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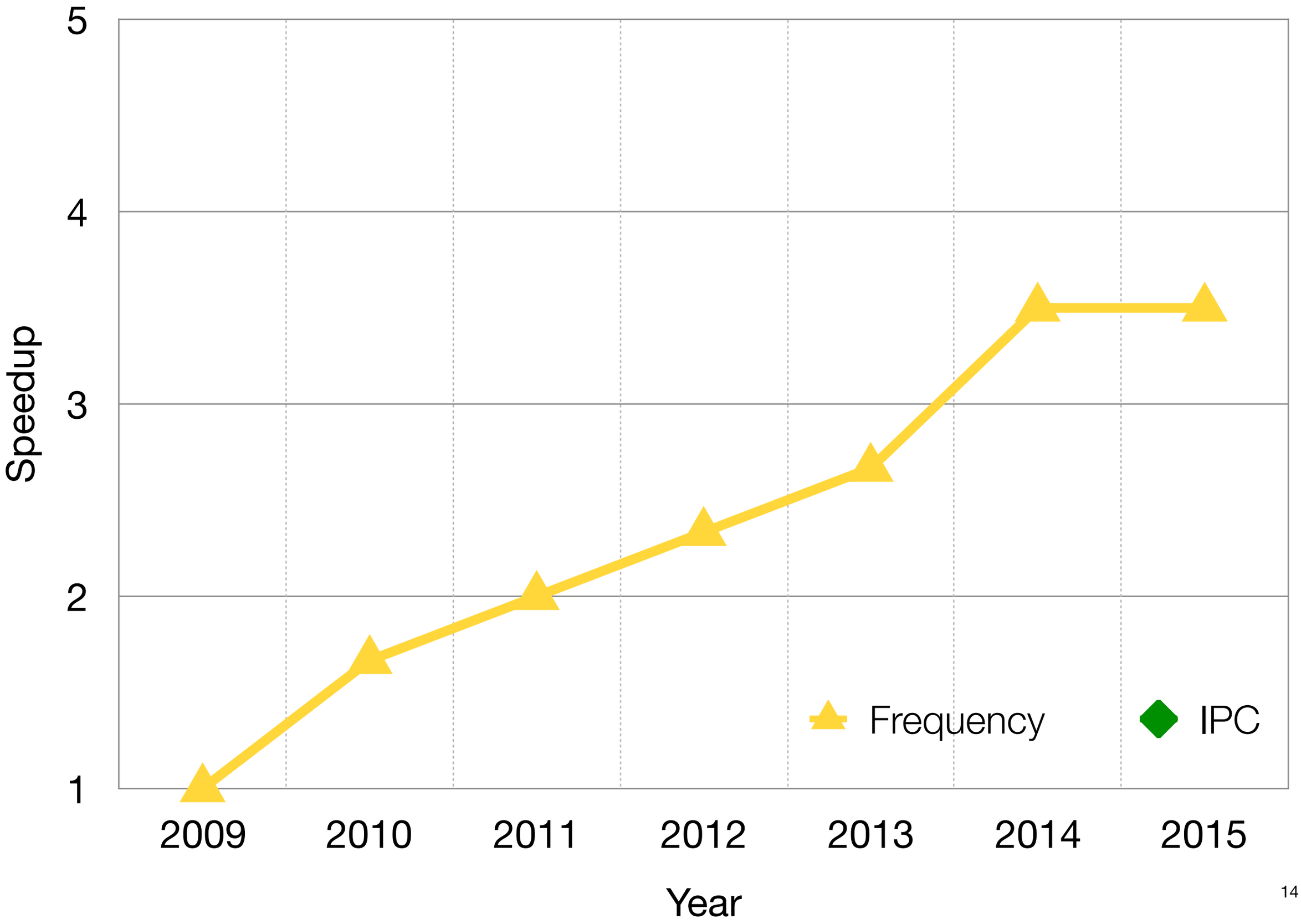

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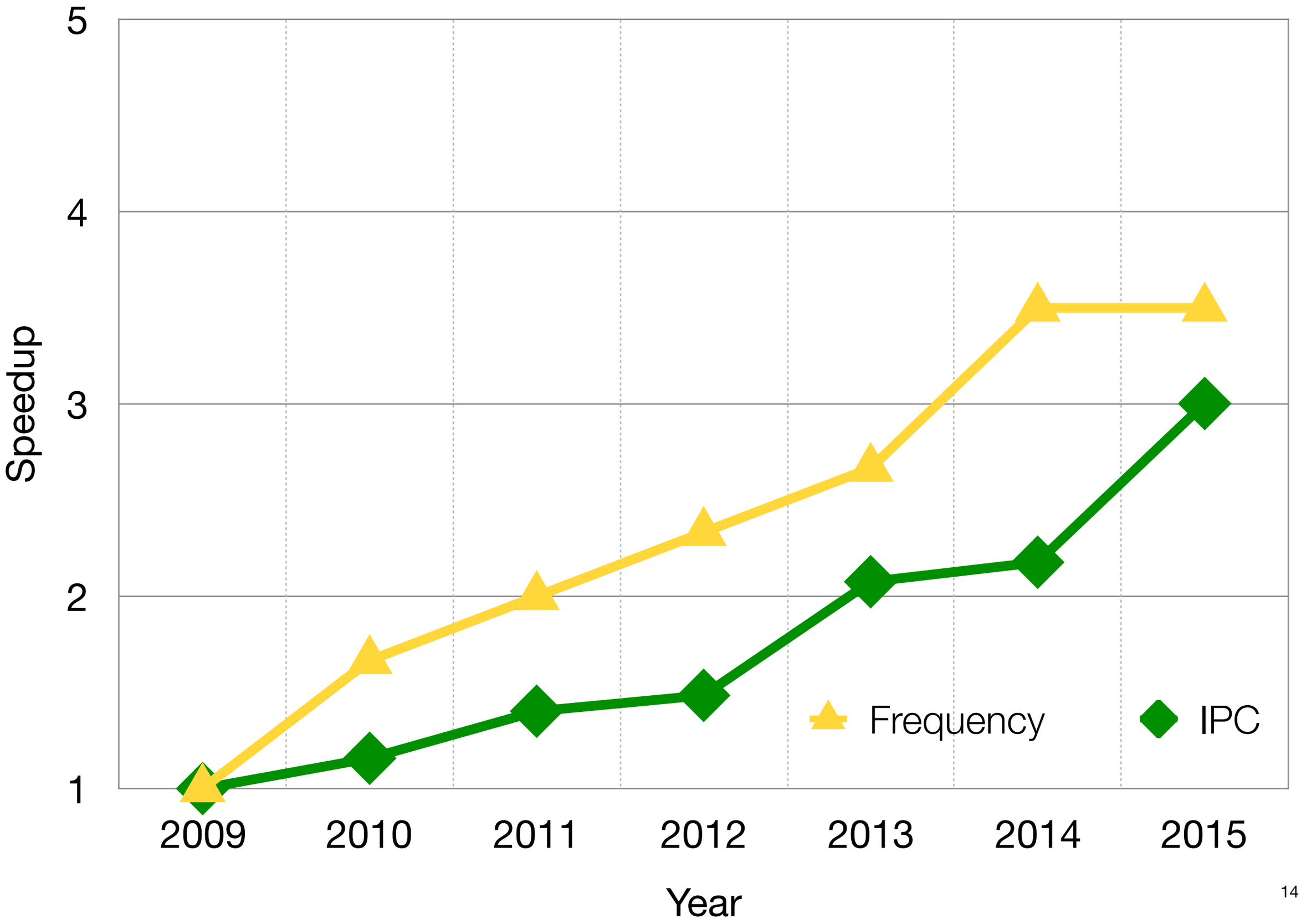

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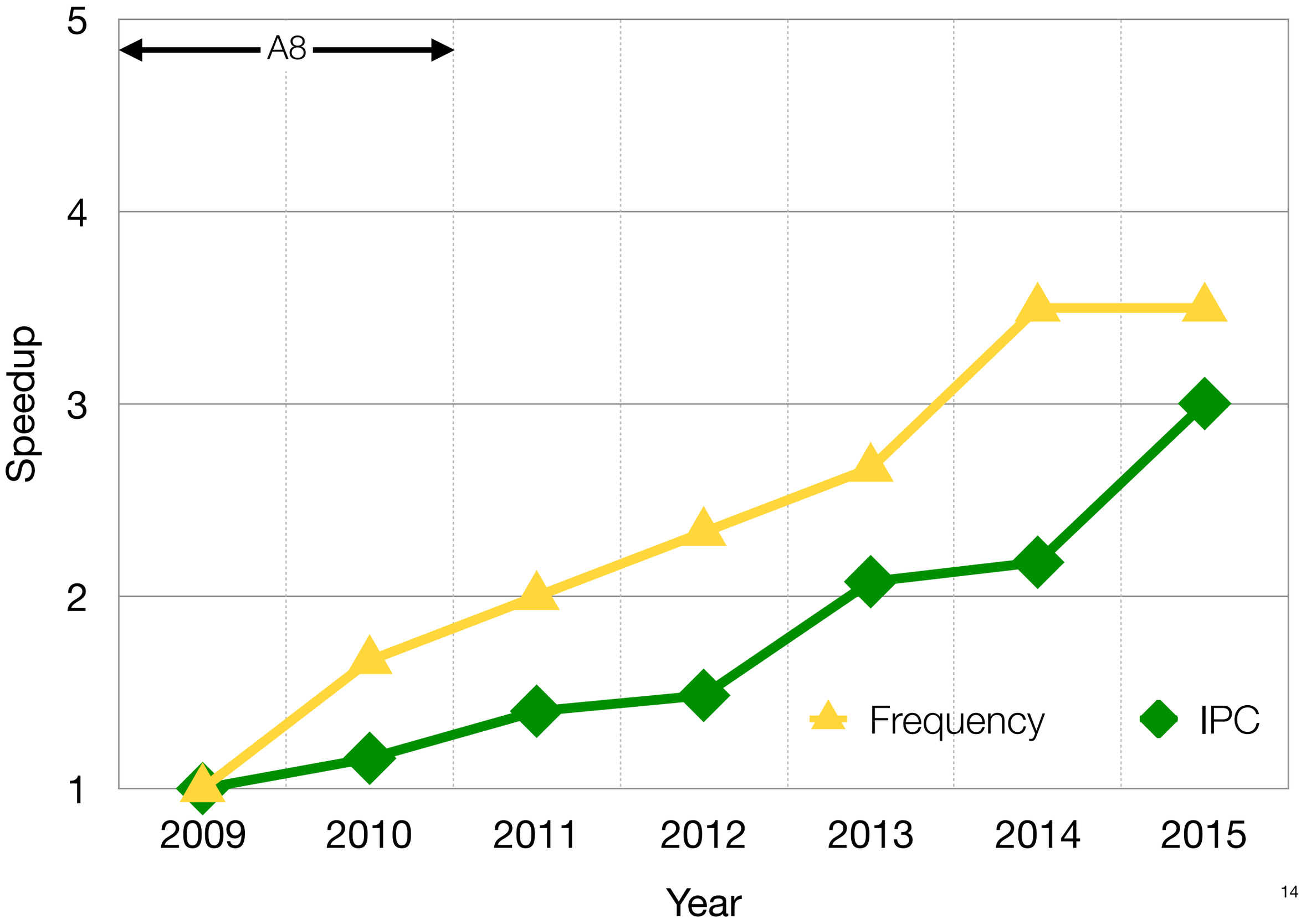

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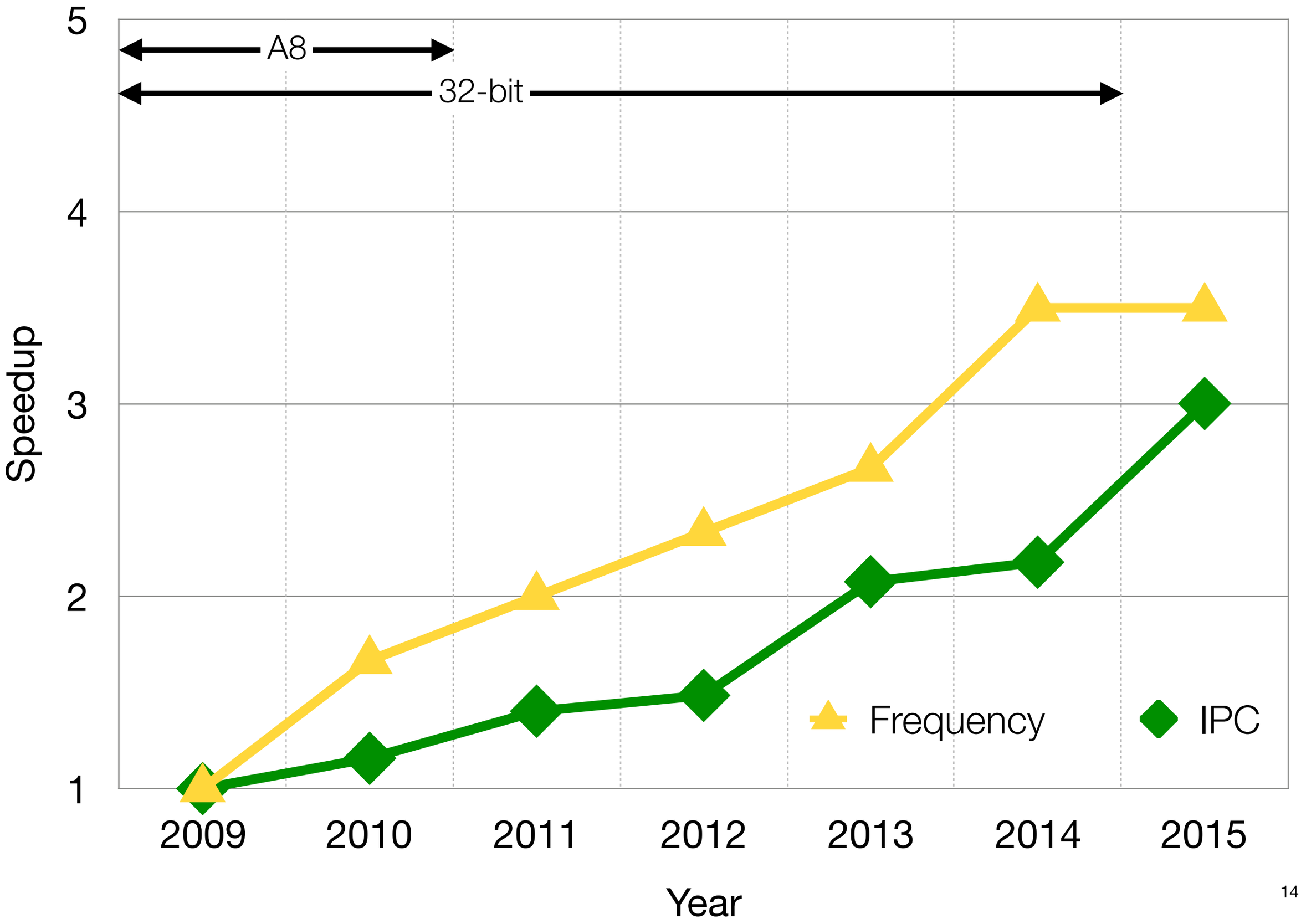

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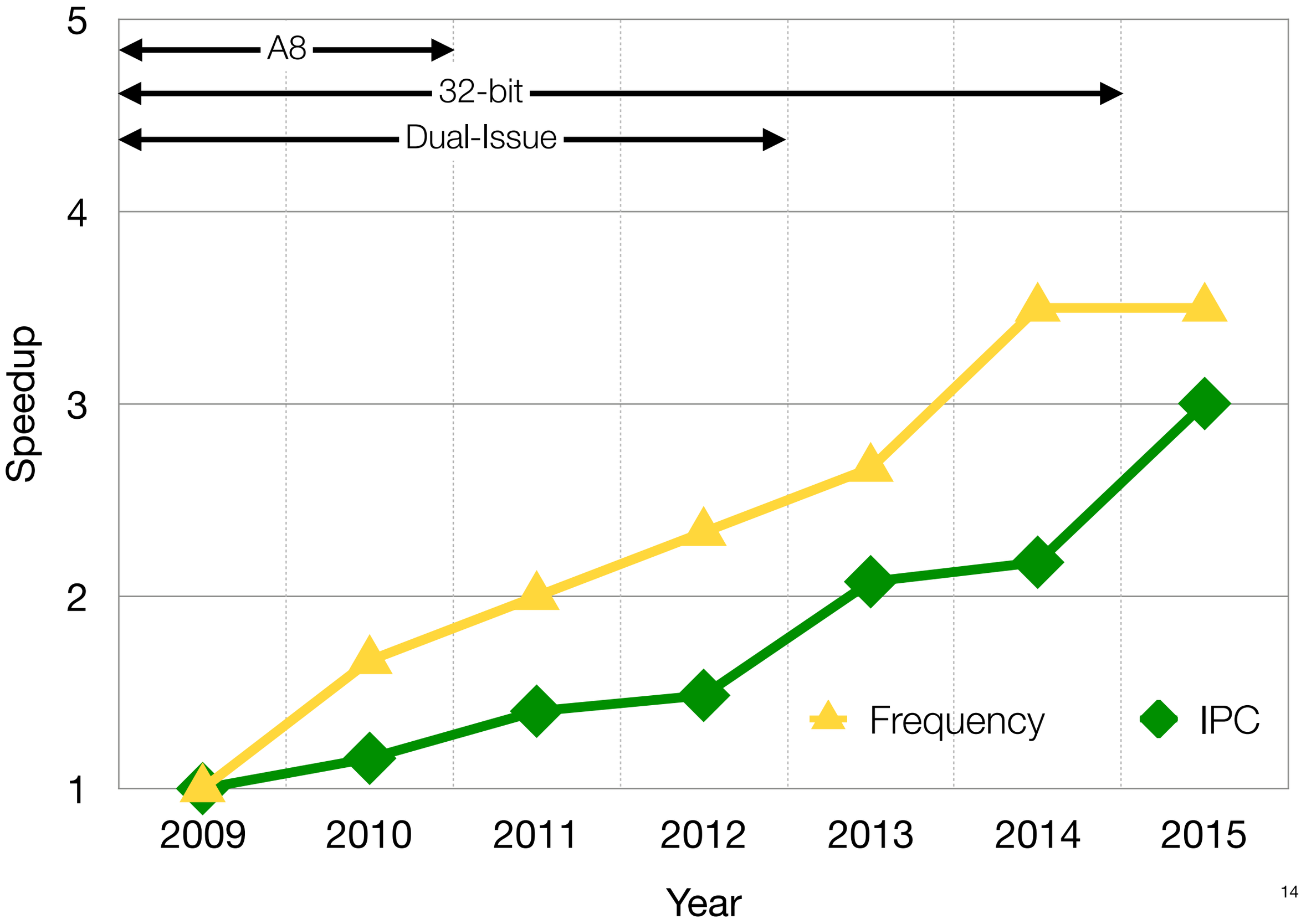

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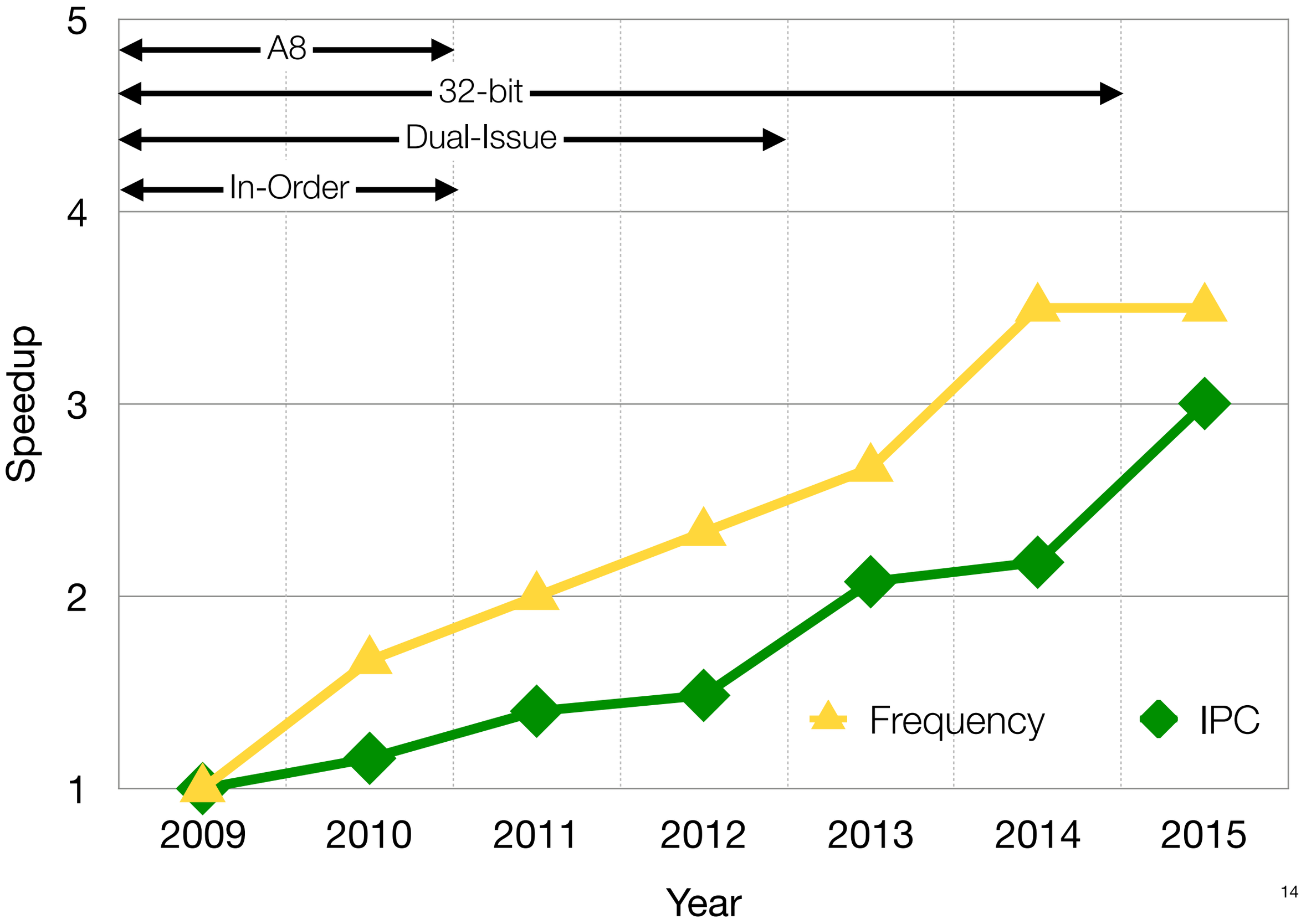

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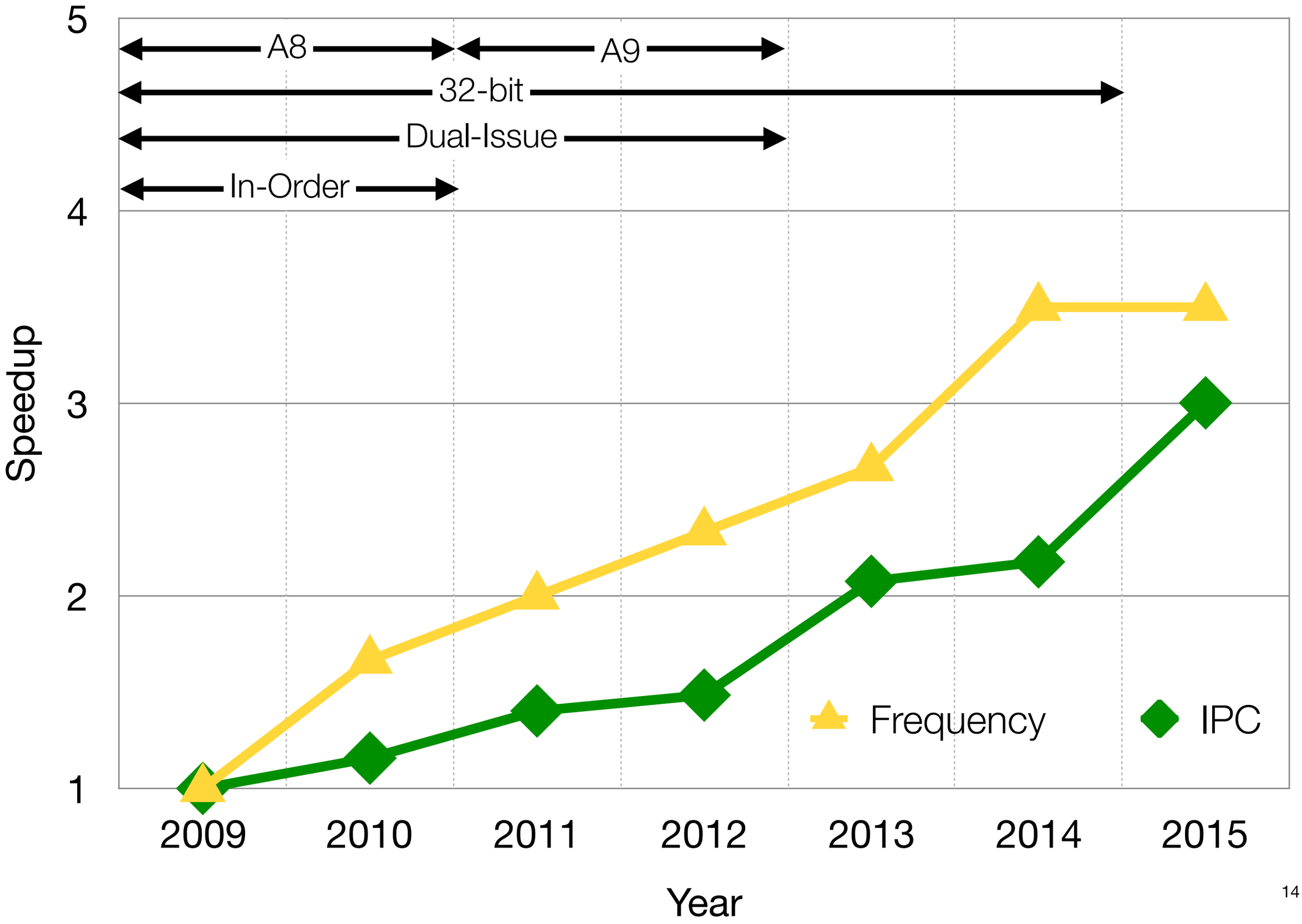

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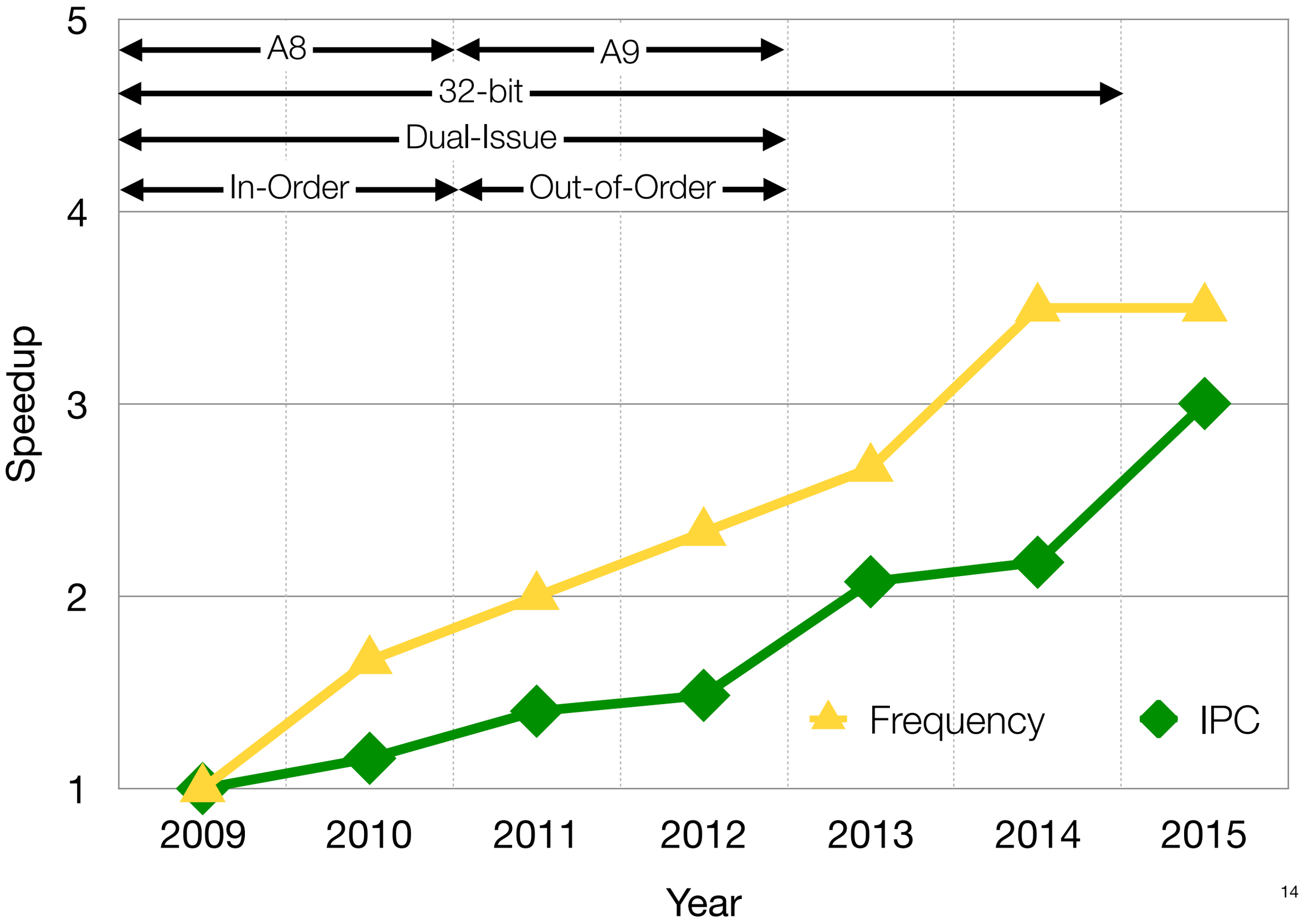

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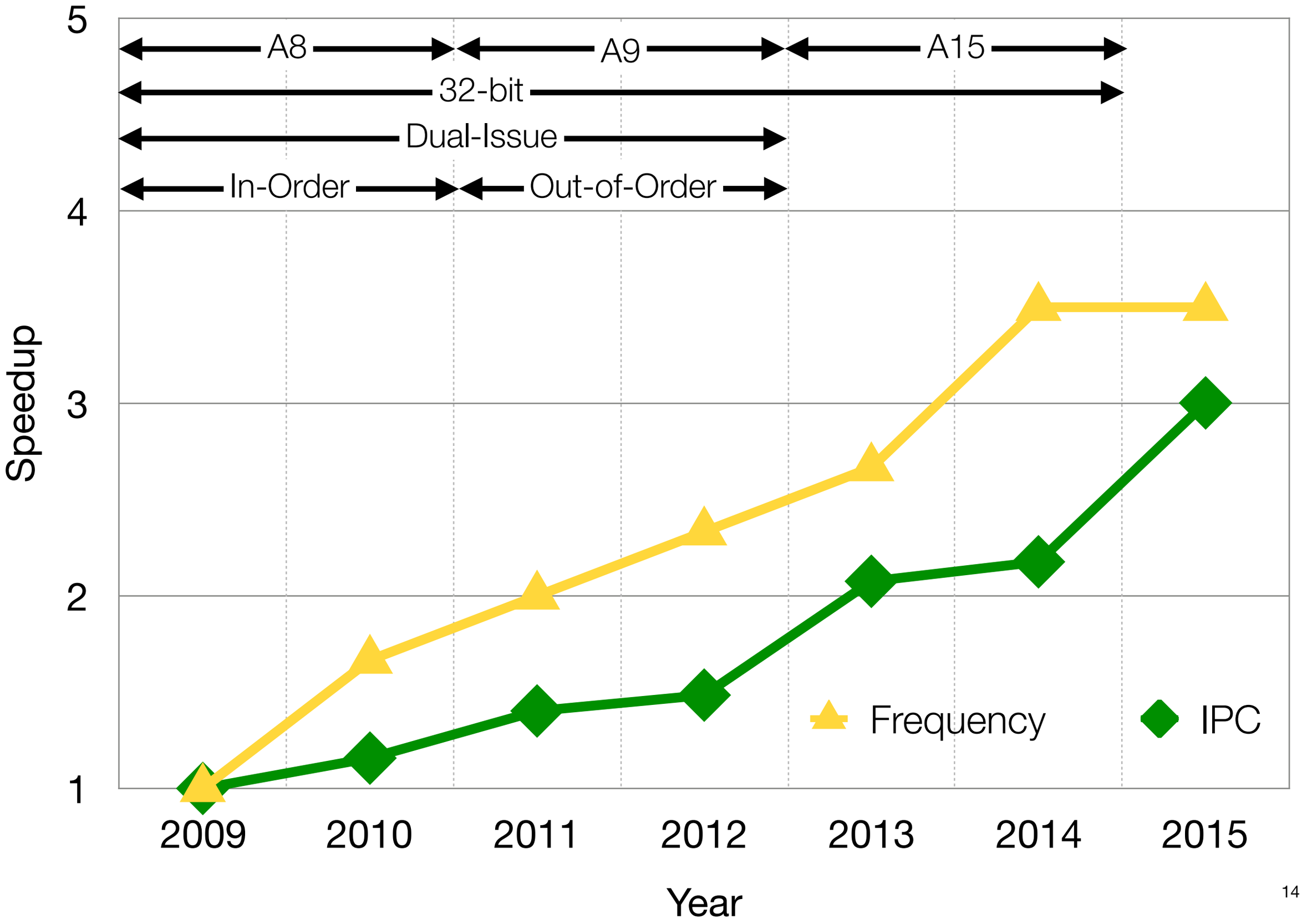

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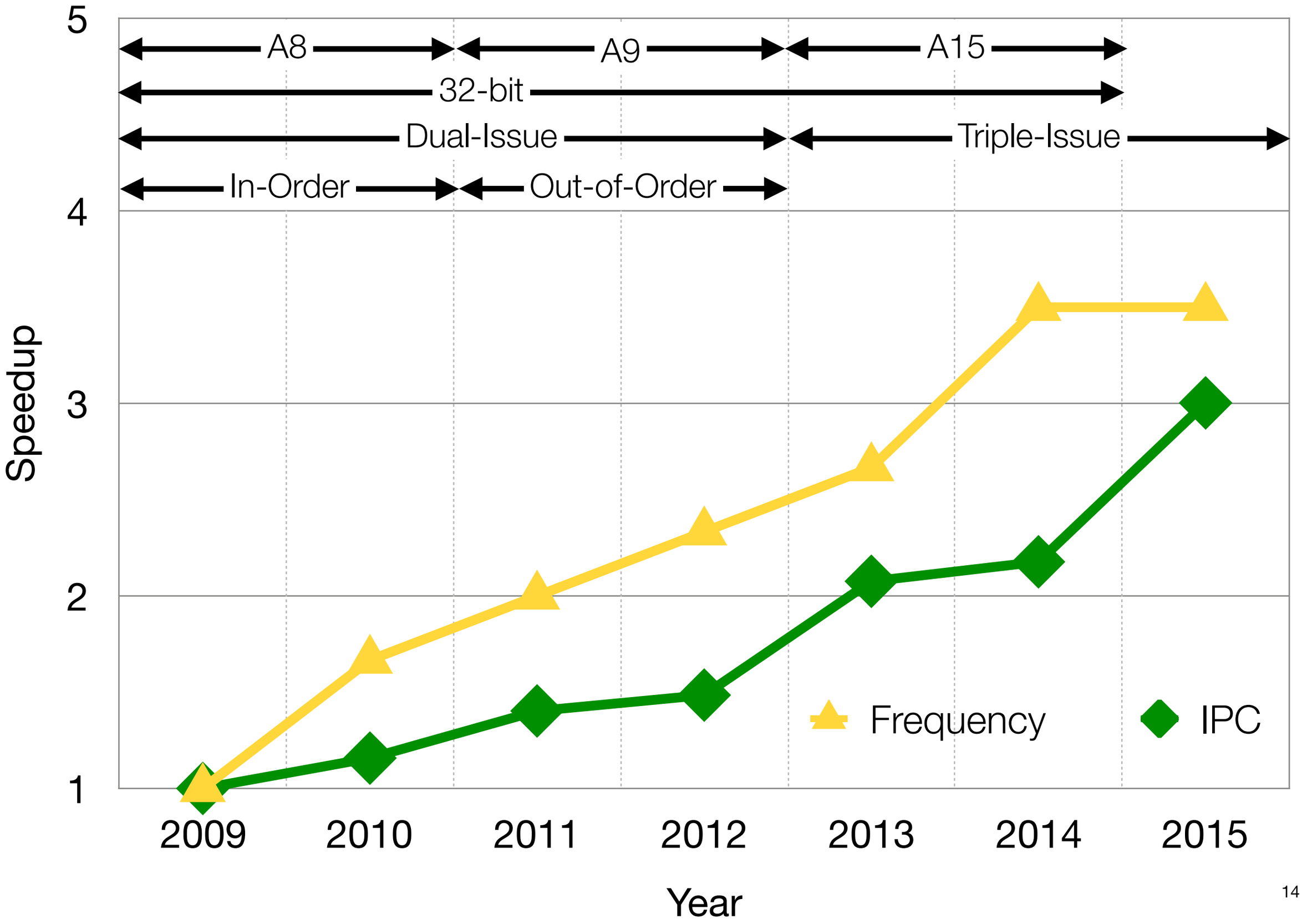

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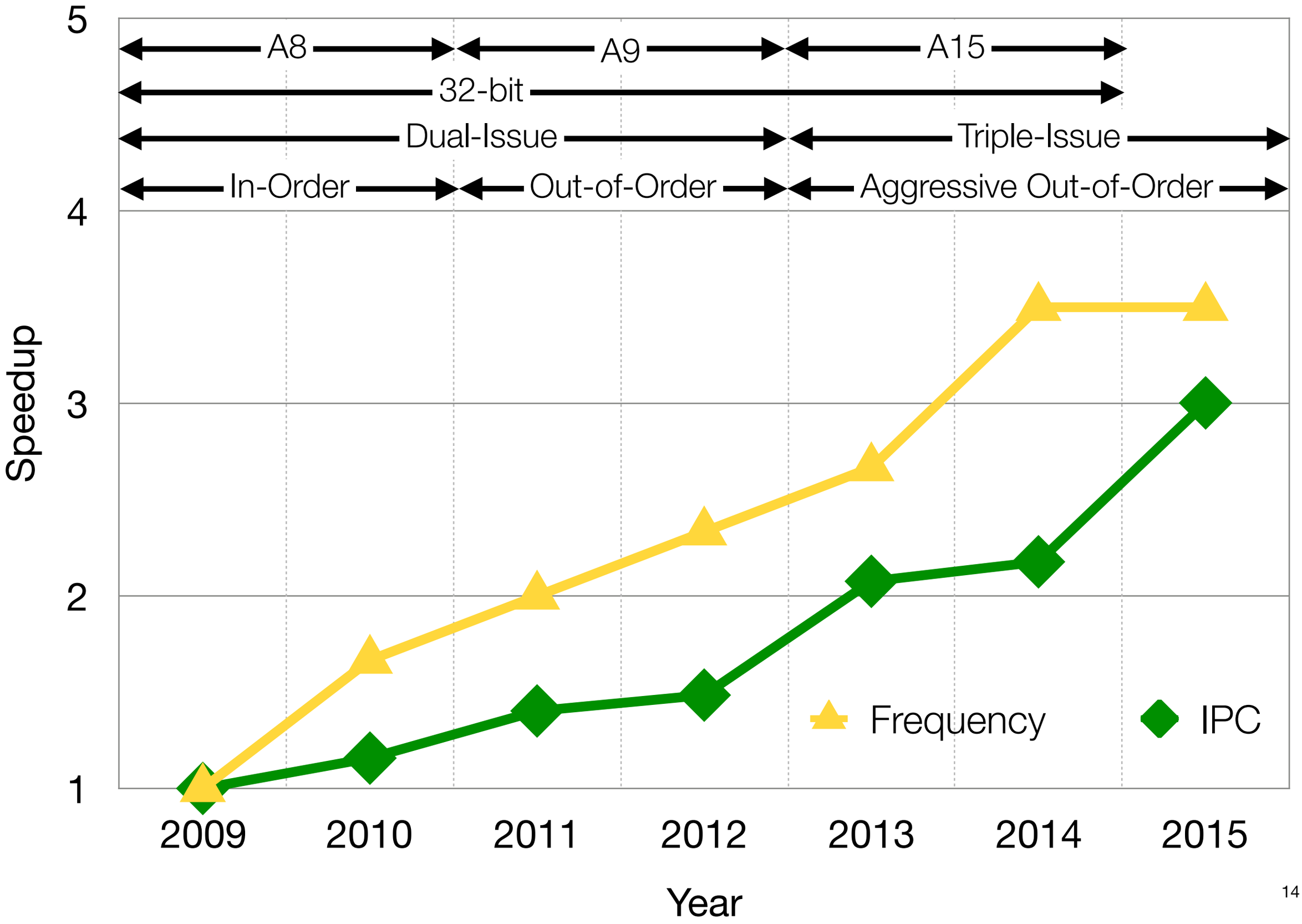

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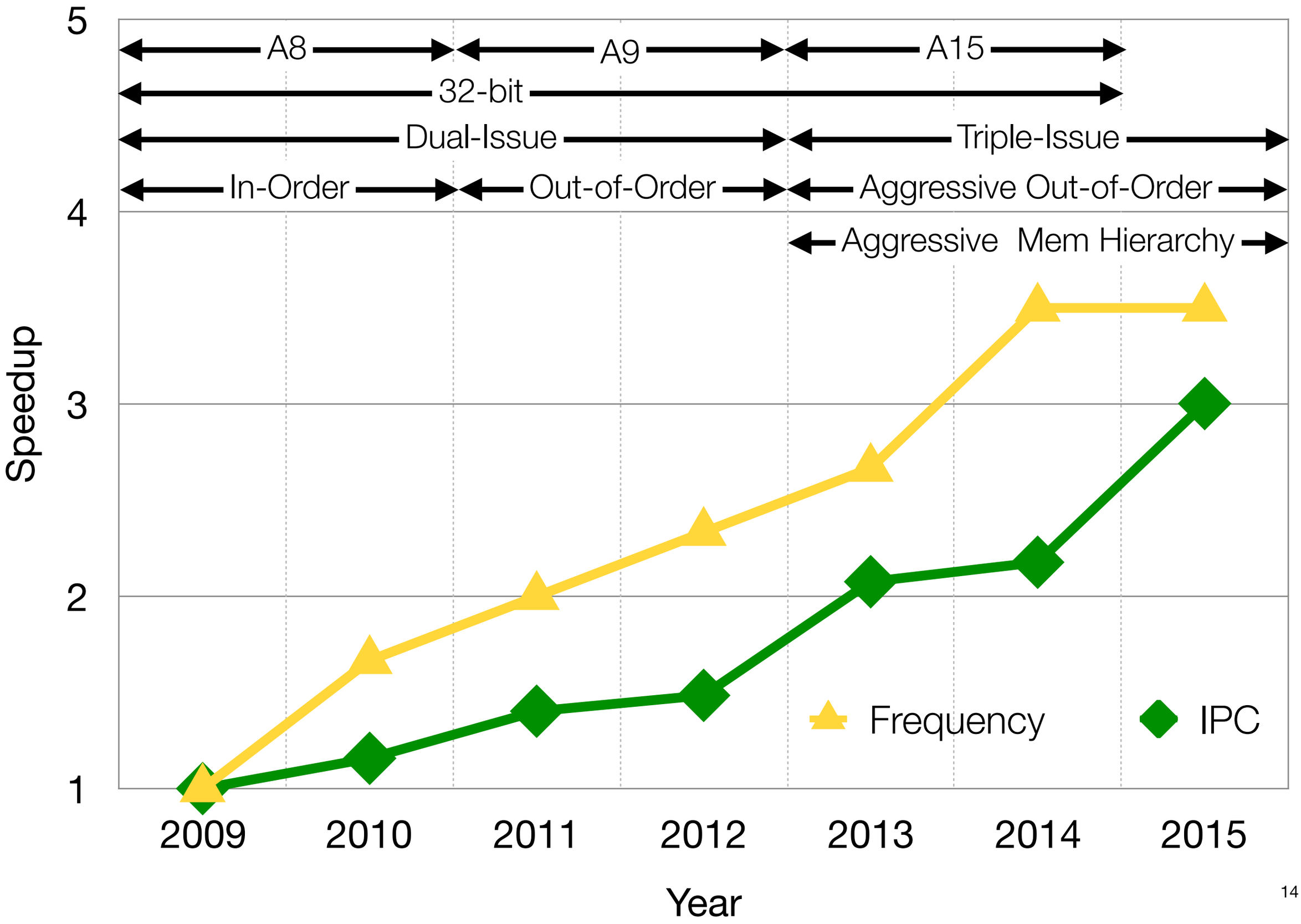

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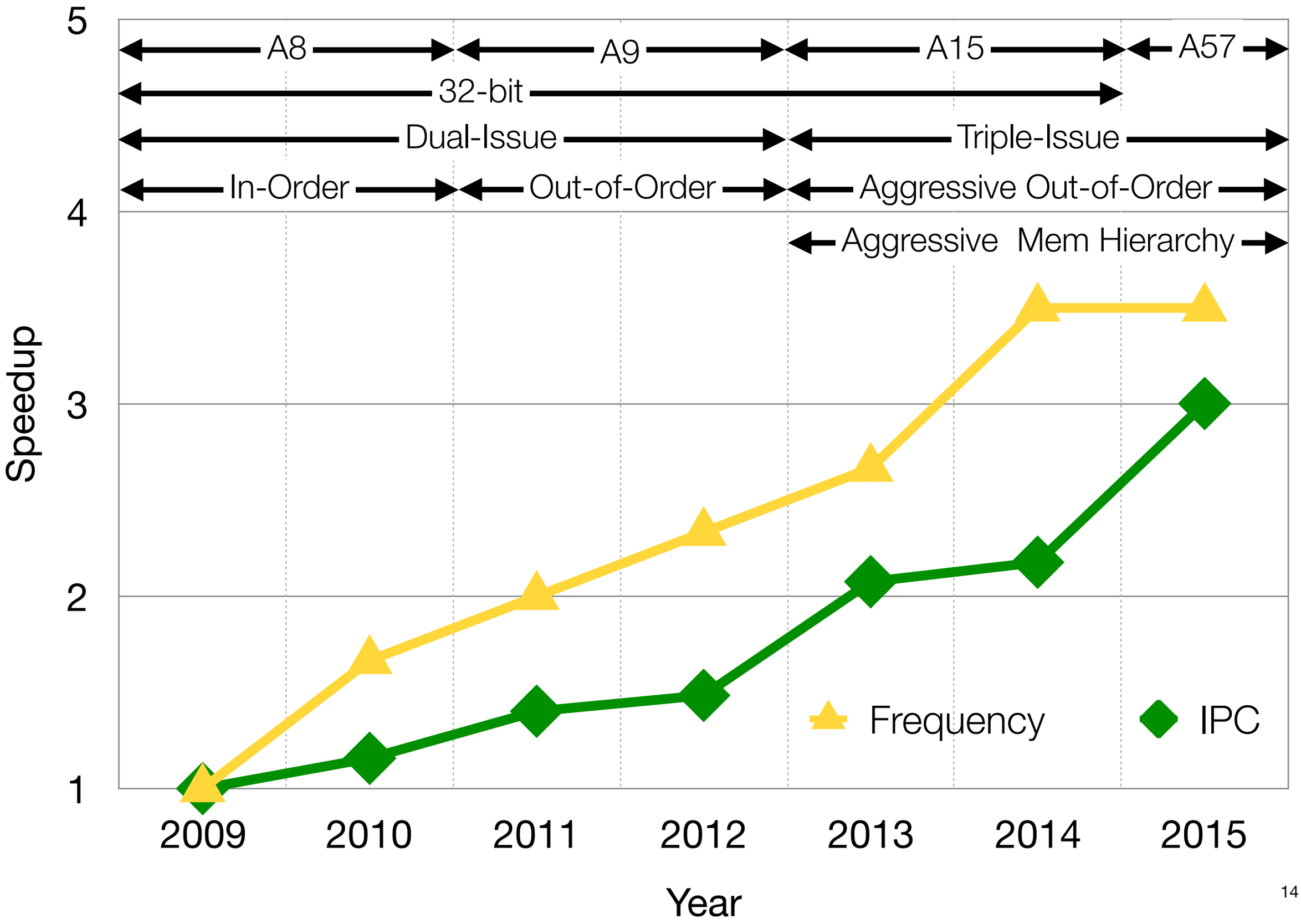

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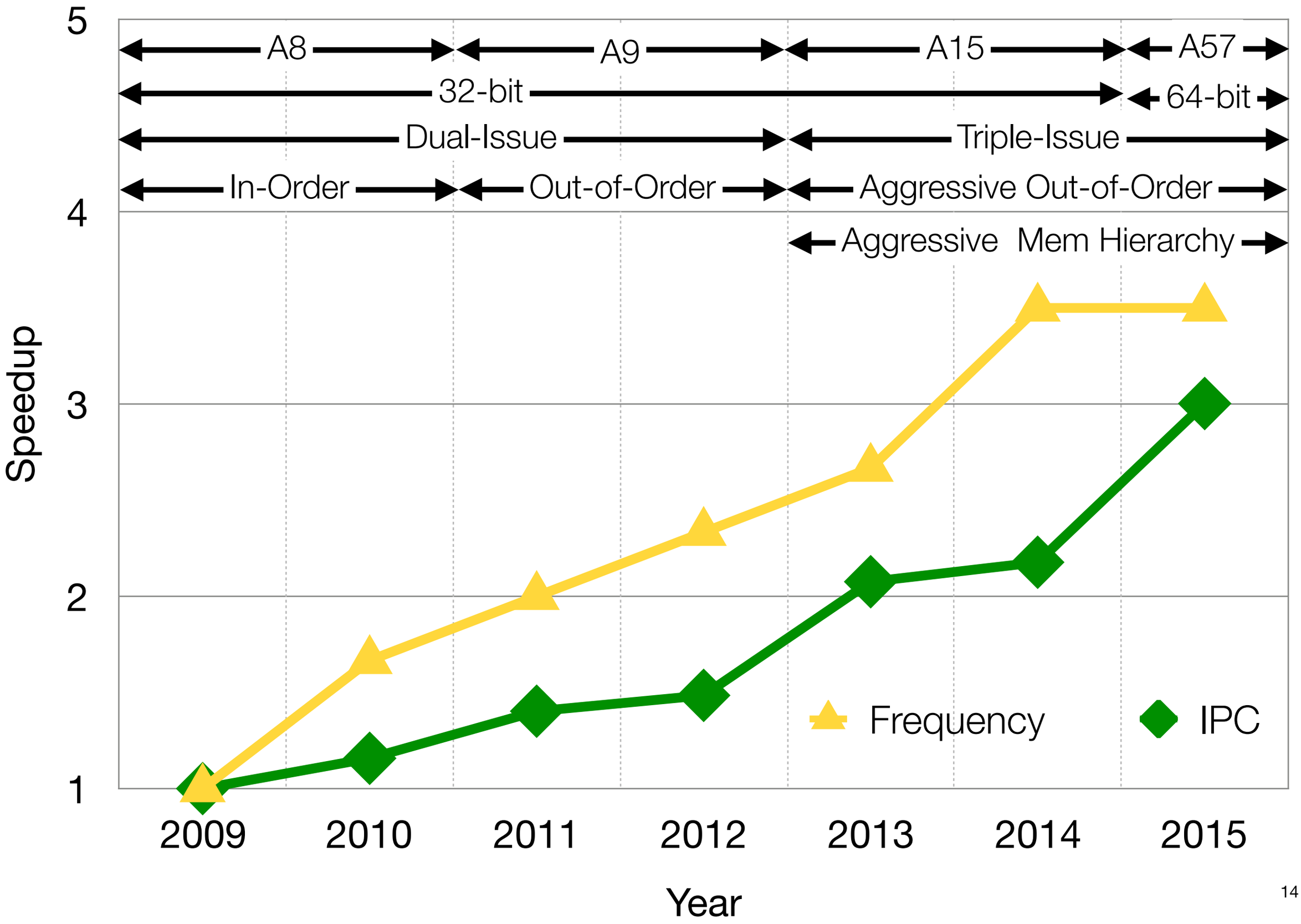

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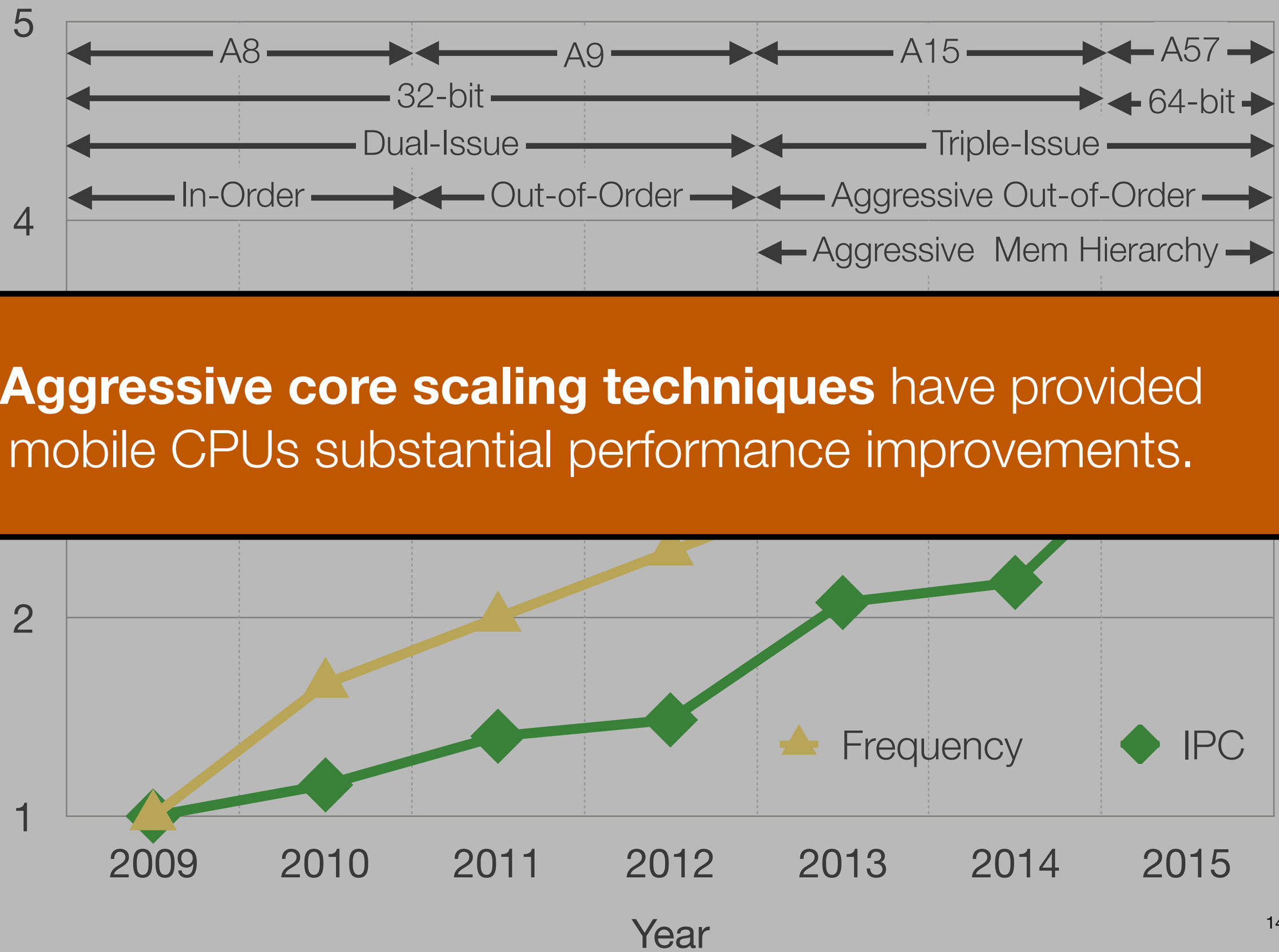
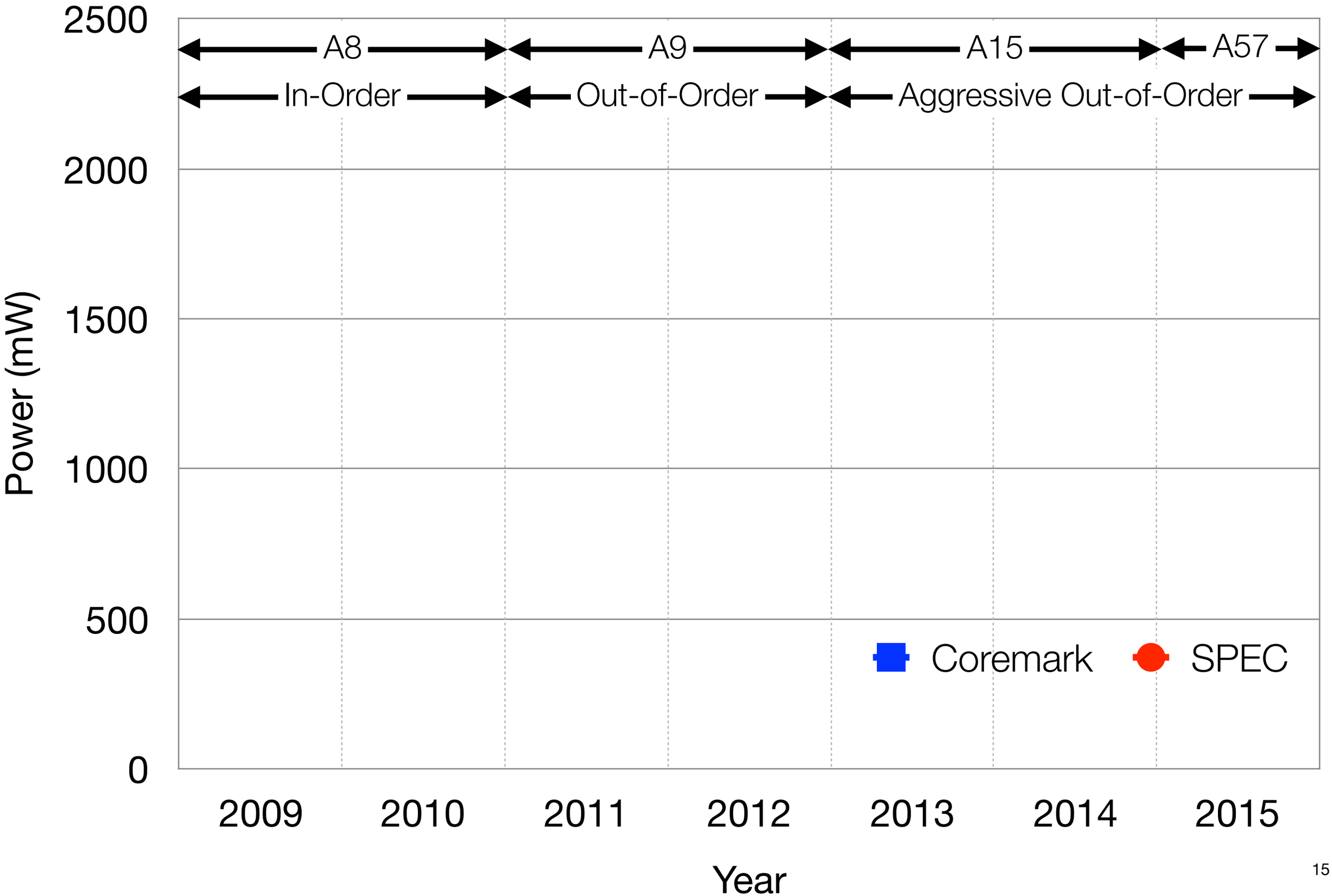


Aggressive core scaling techniques have provided mobile CPUs substantial performance improvements.

Excessive Power Consumption

Excessive Power Consumption



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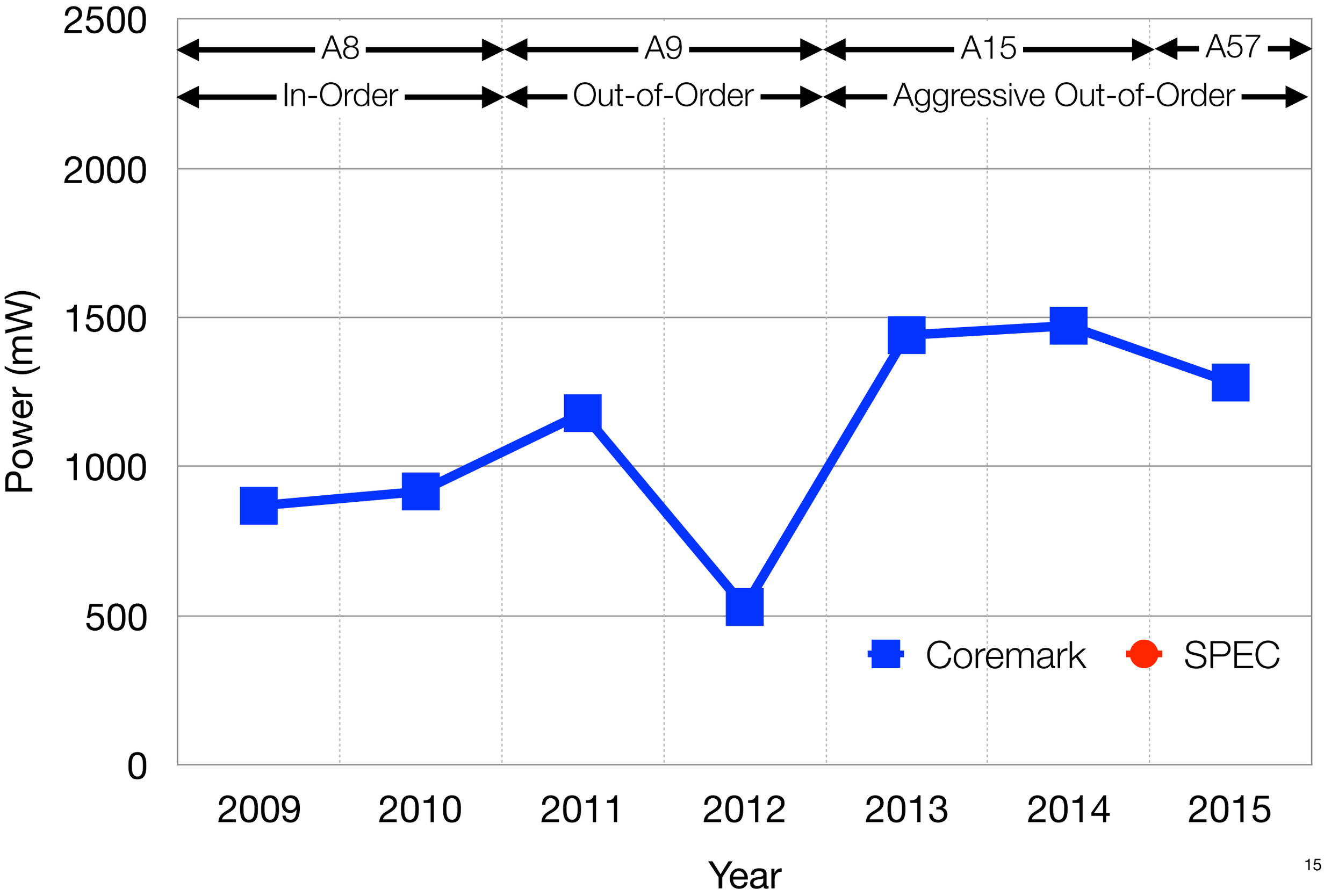

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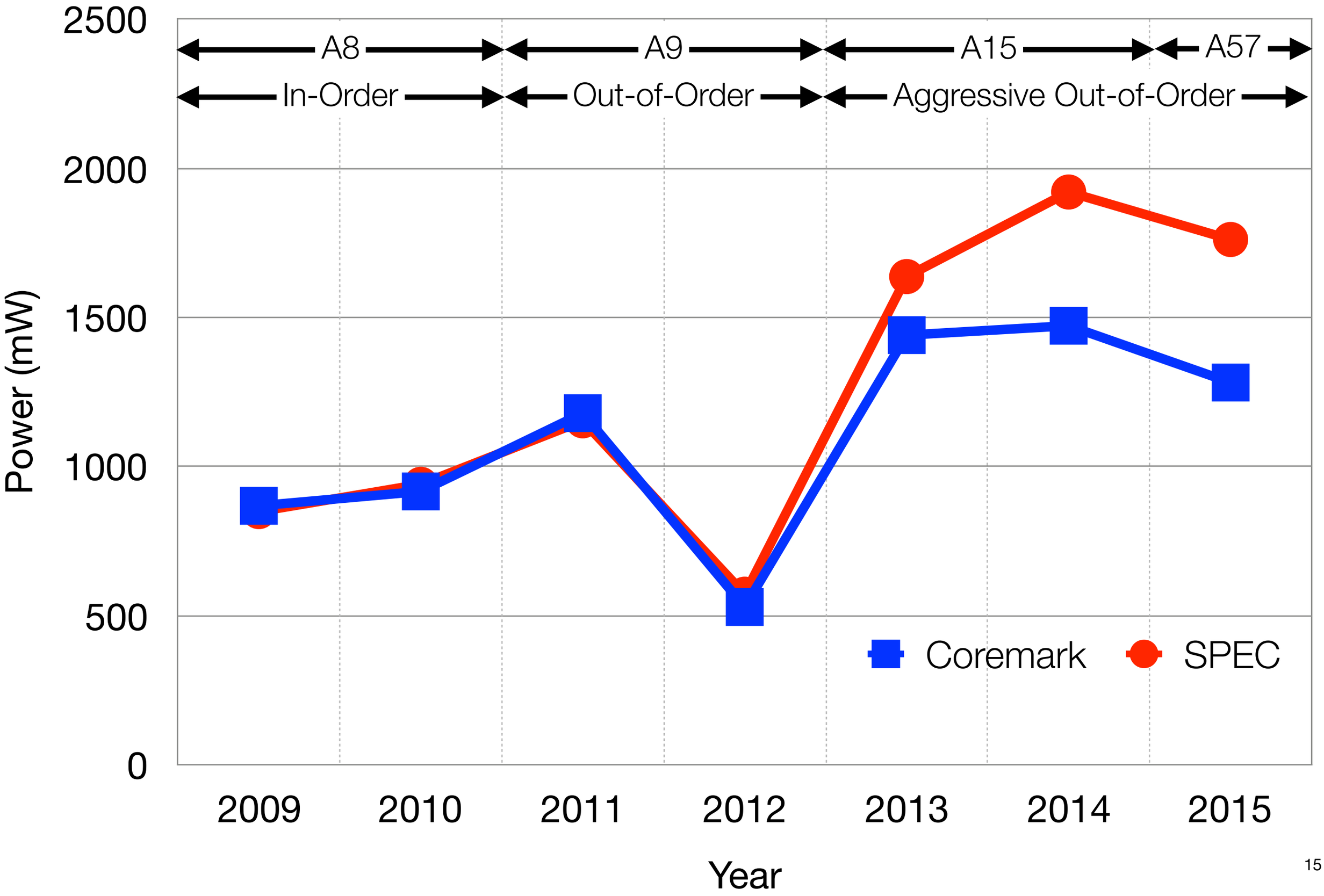

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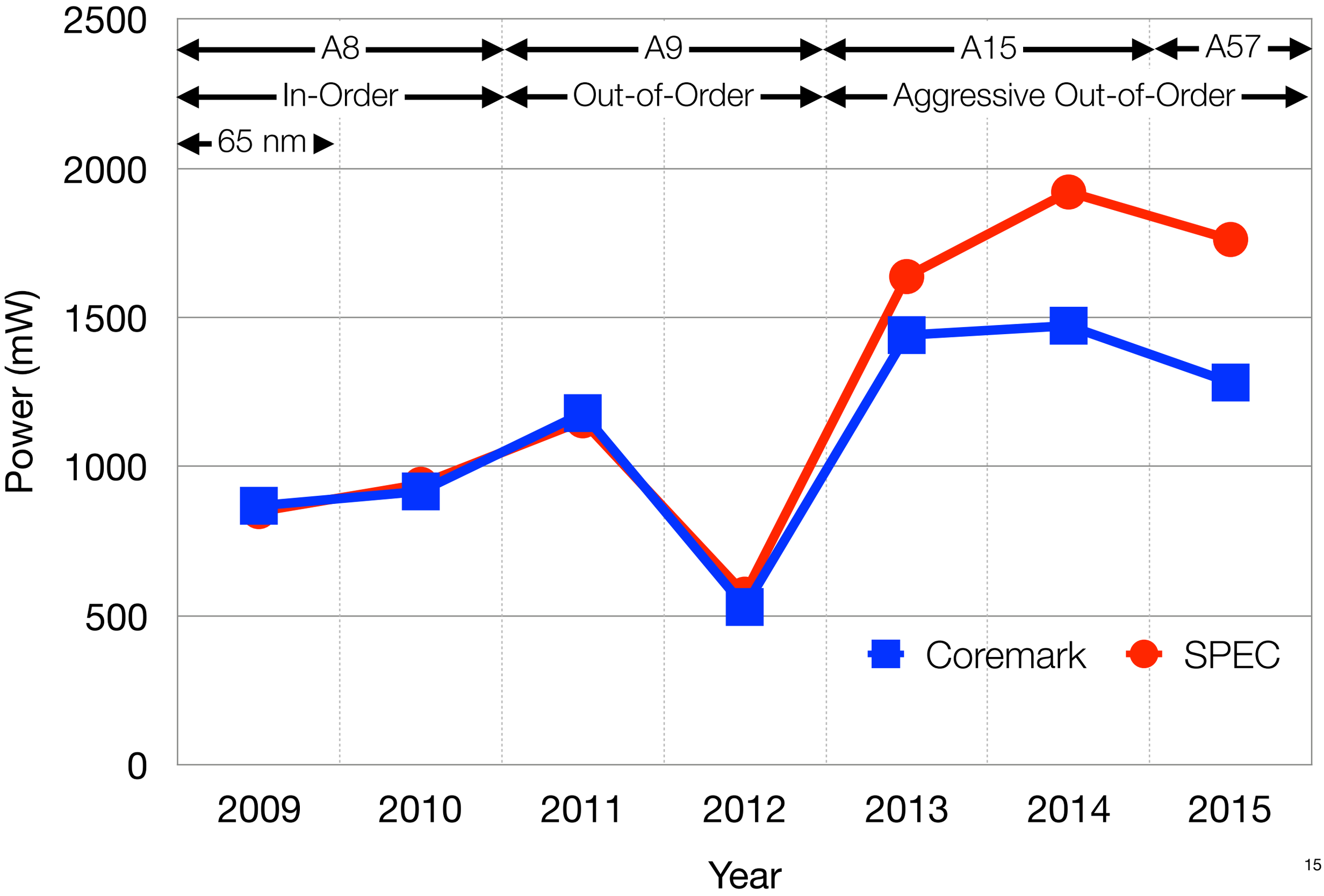

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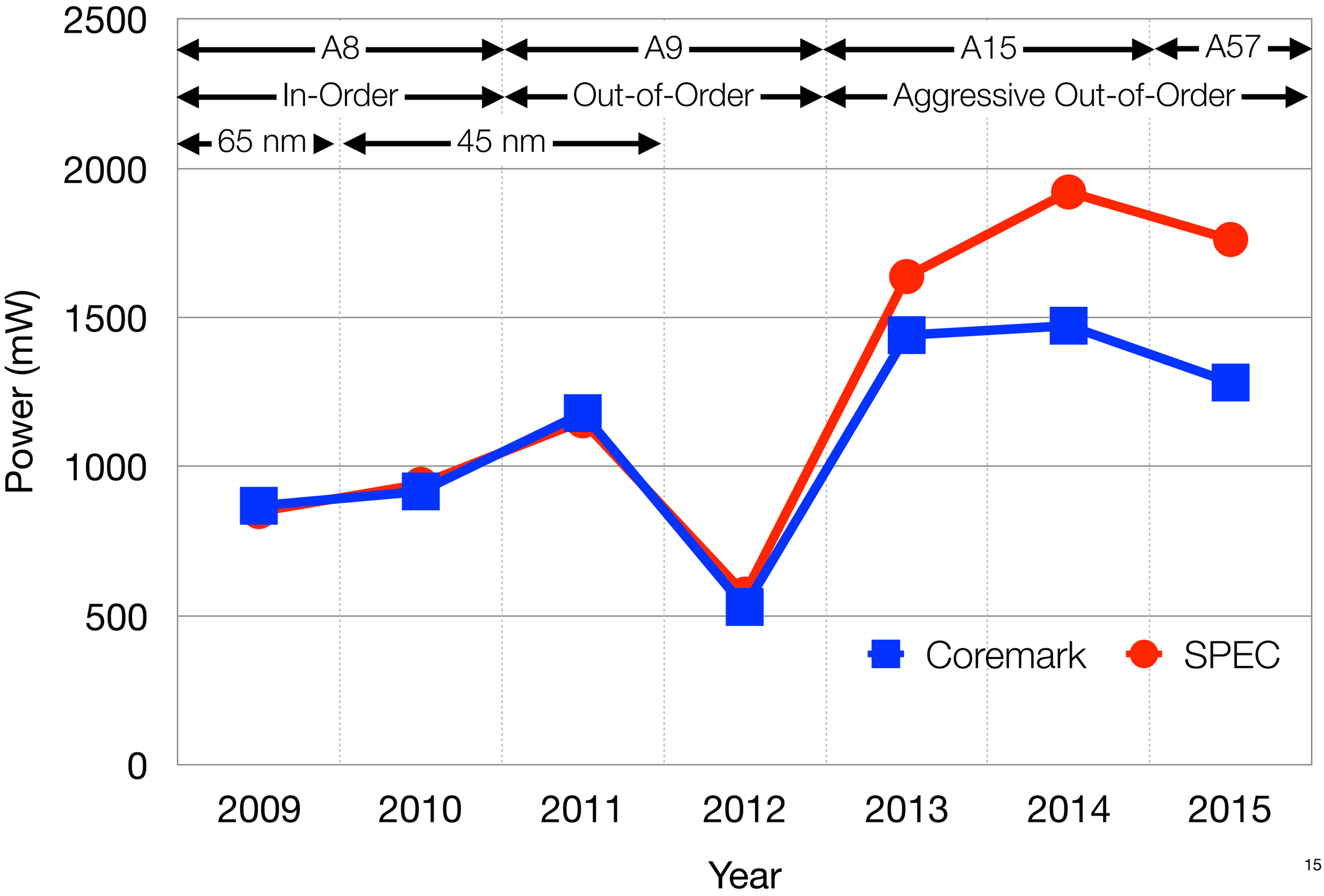

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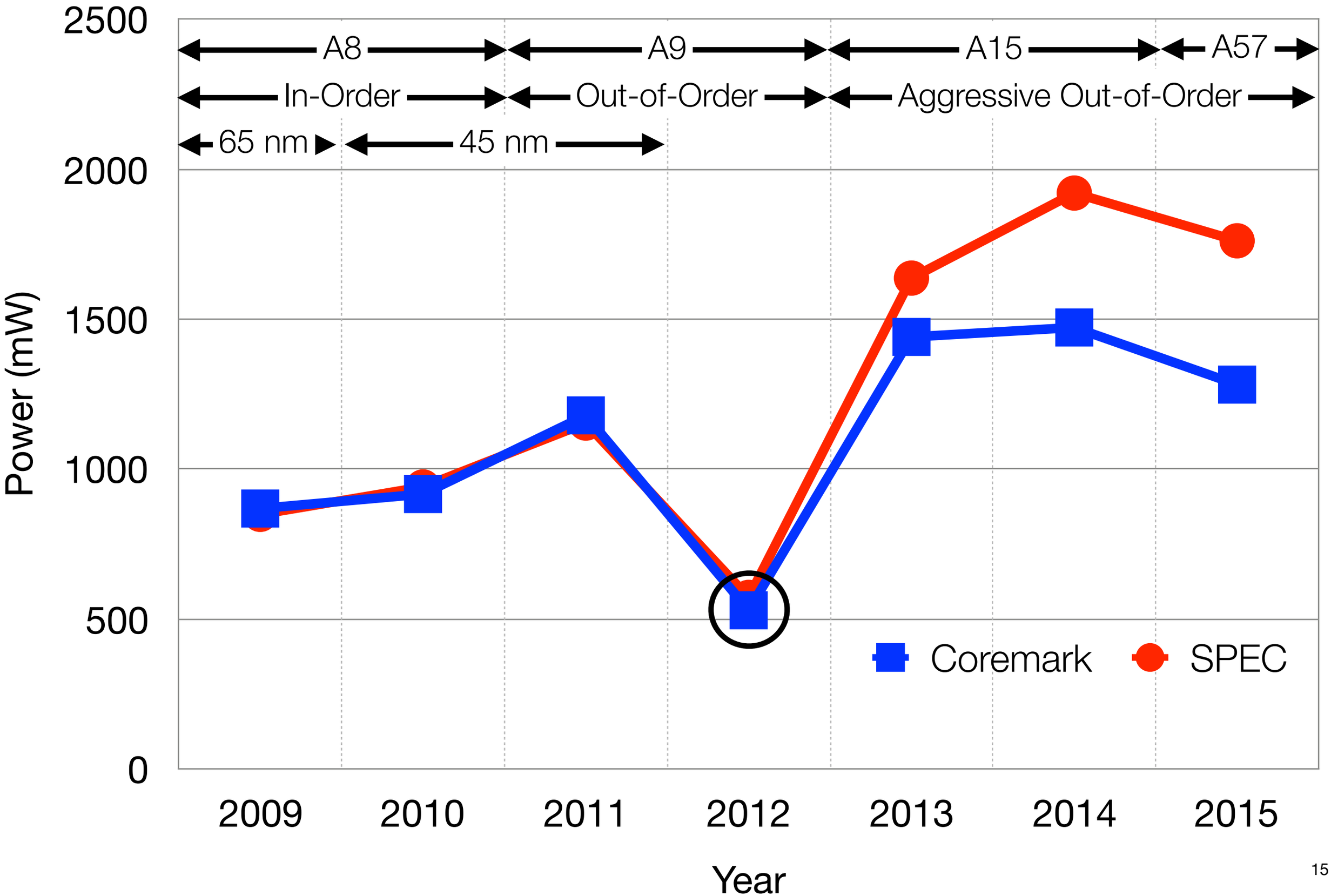

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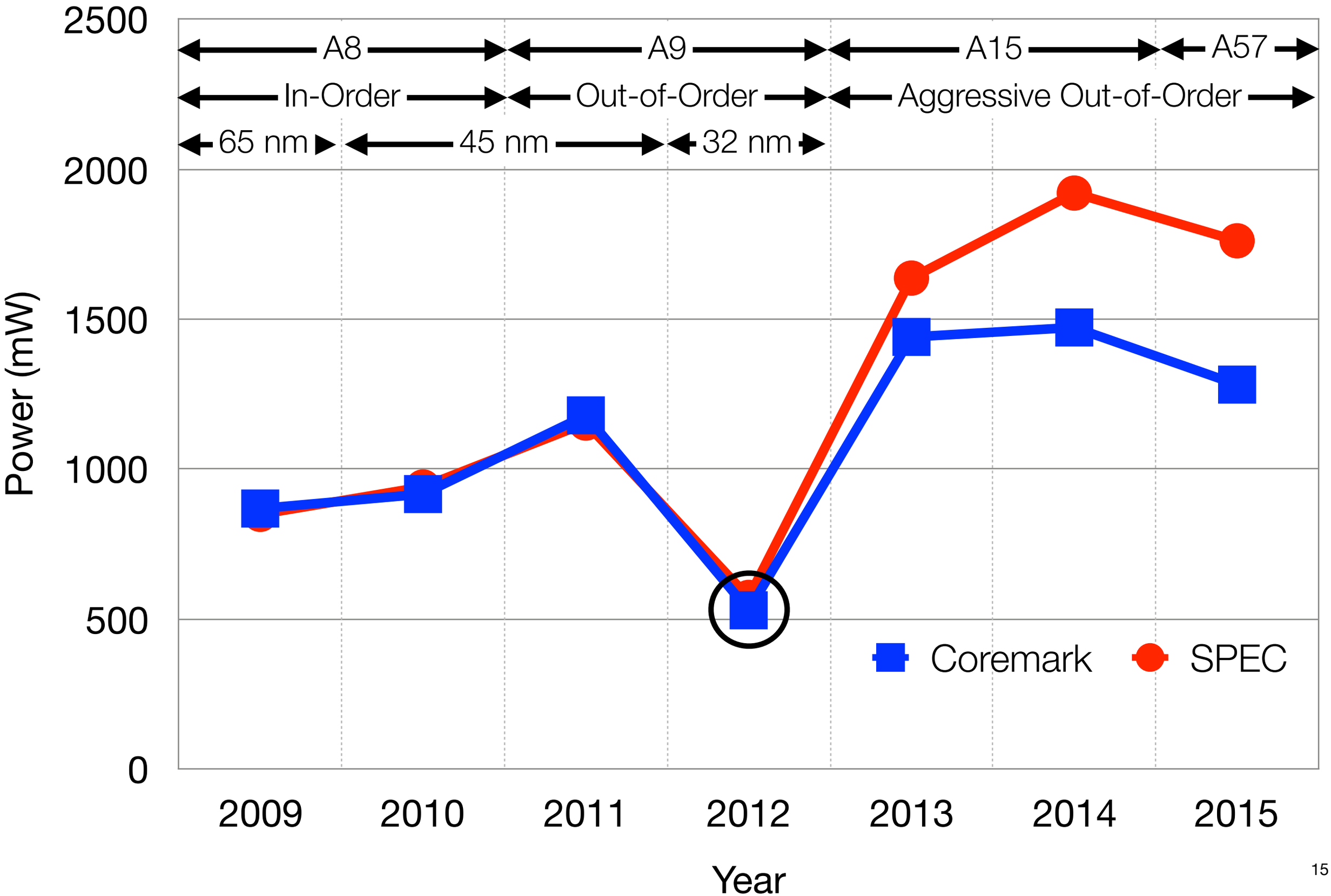

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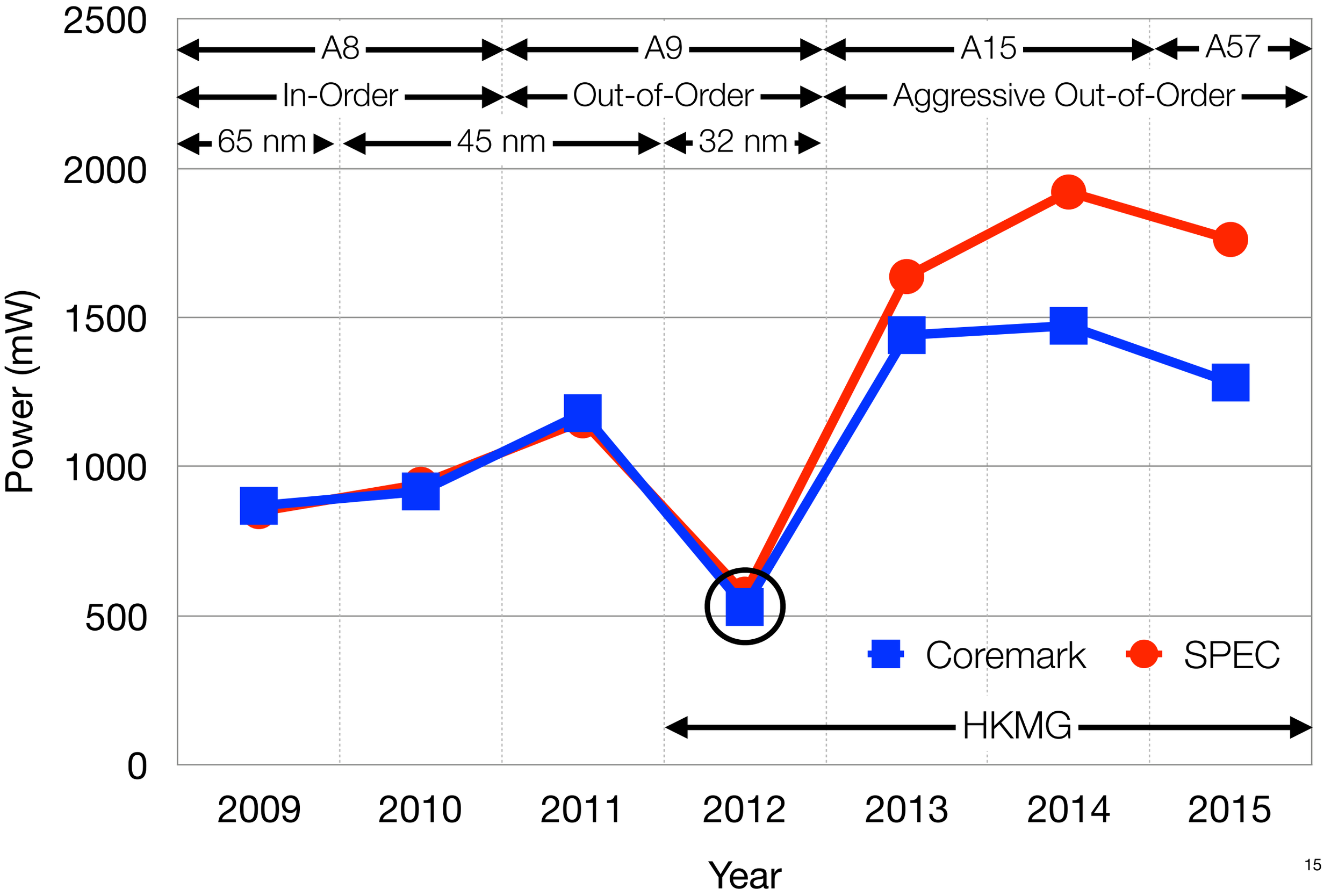

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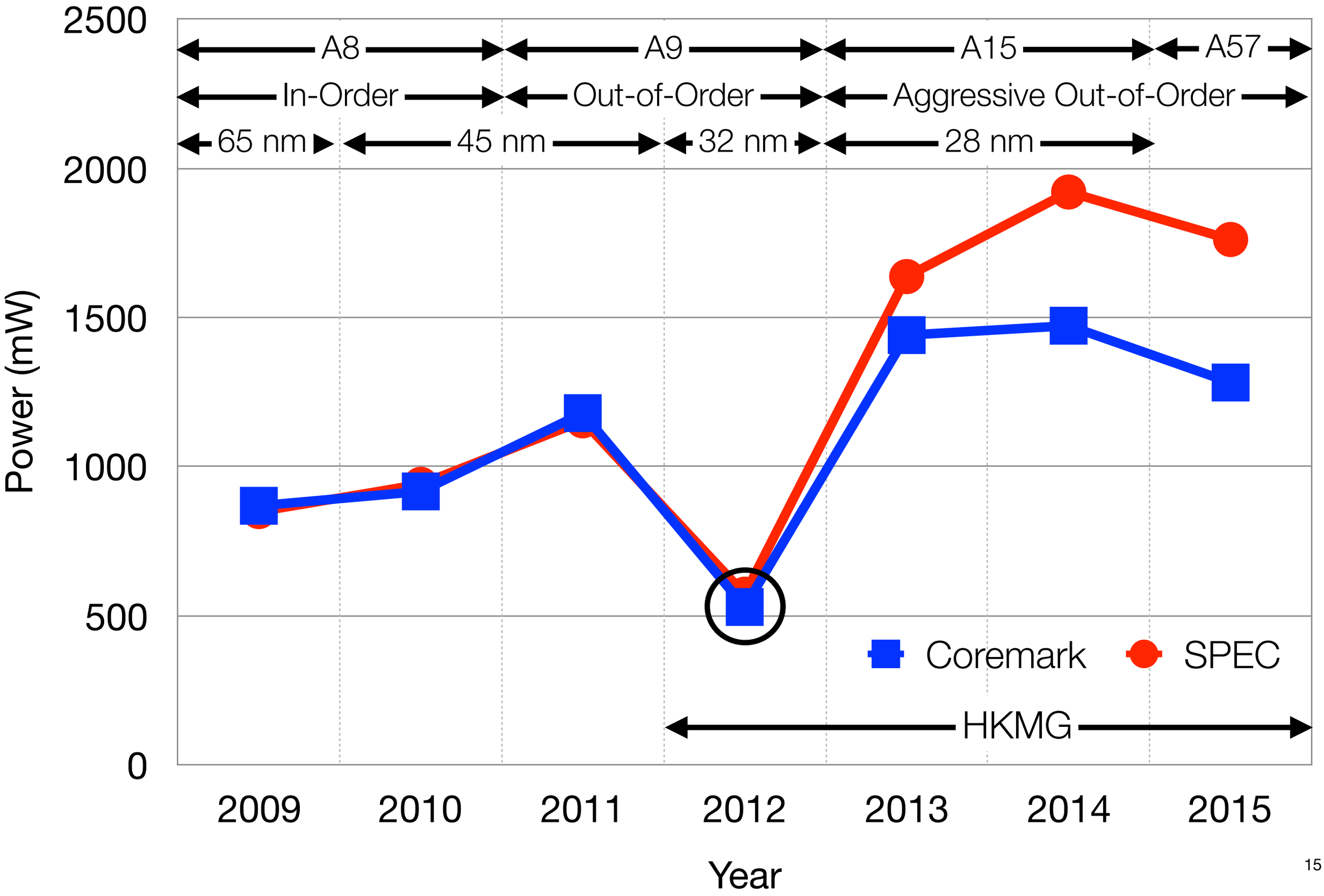

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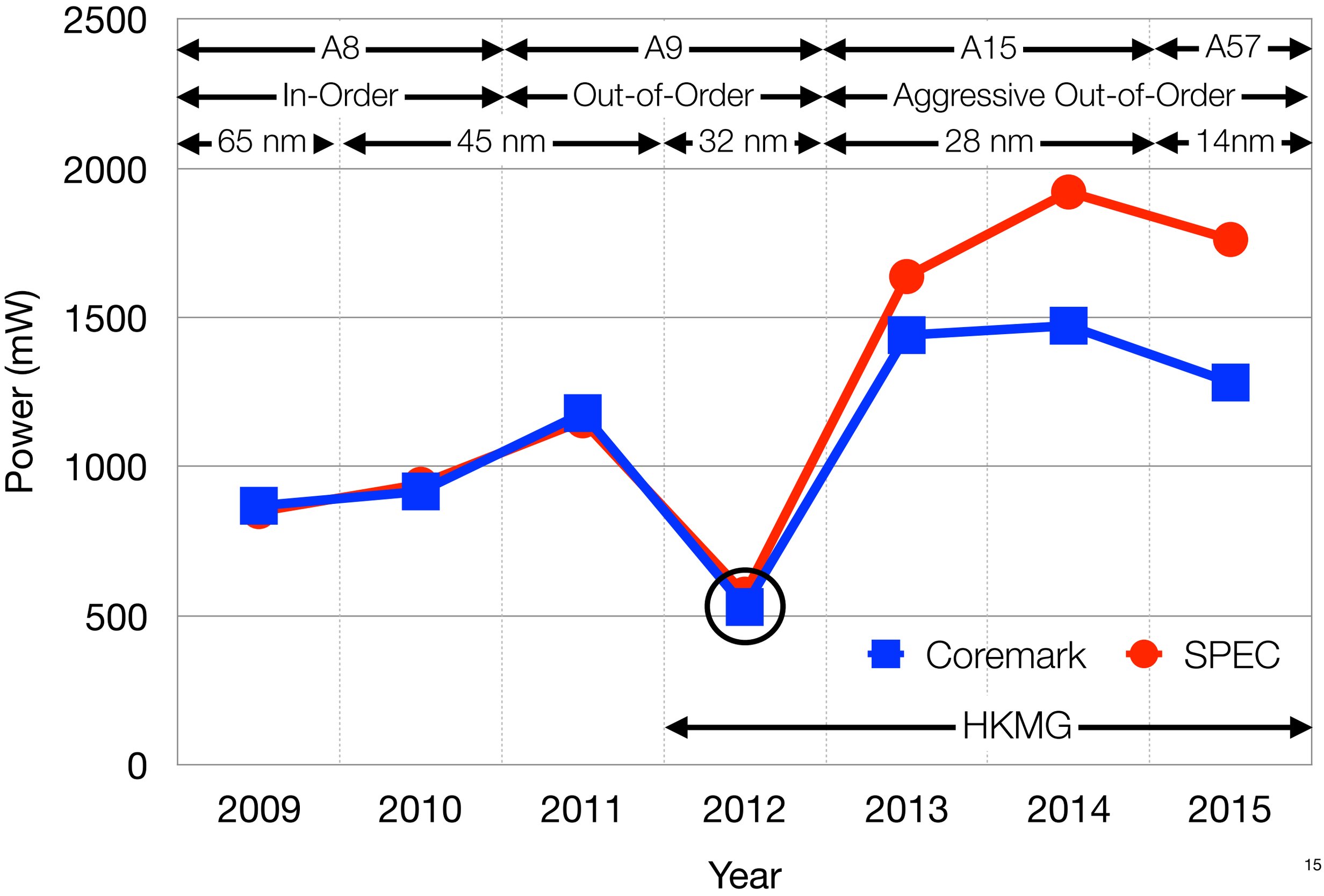

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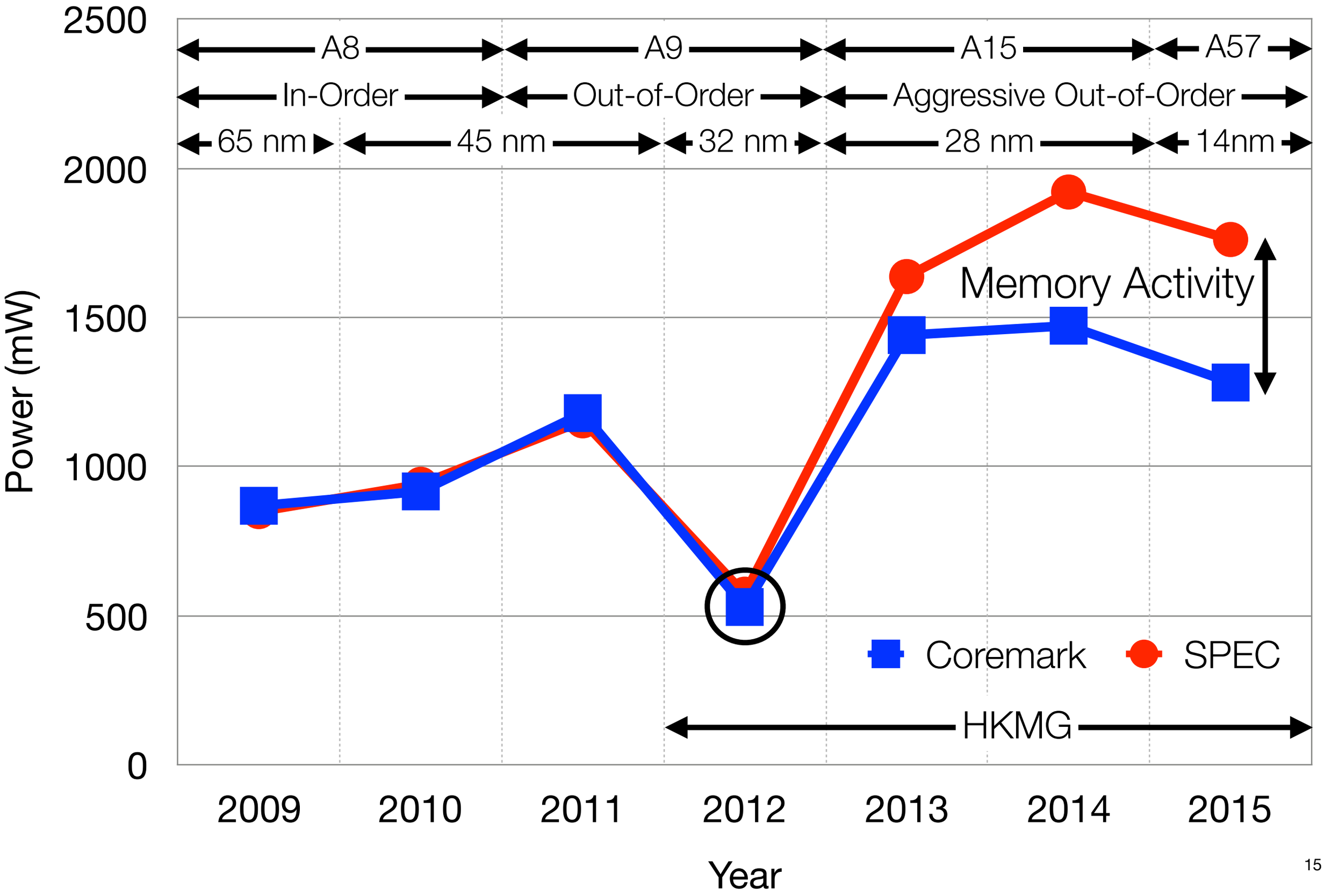

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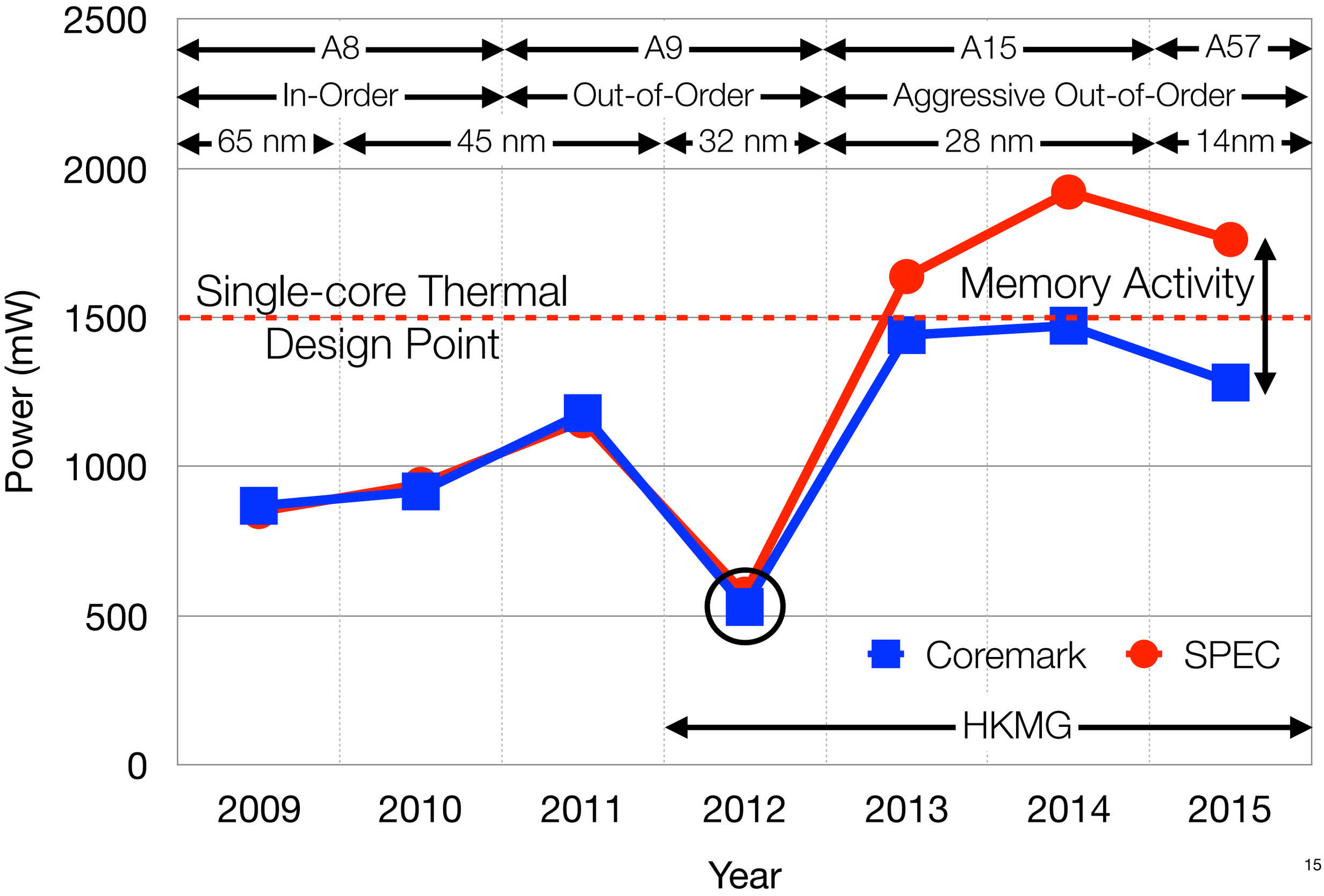

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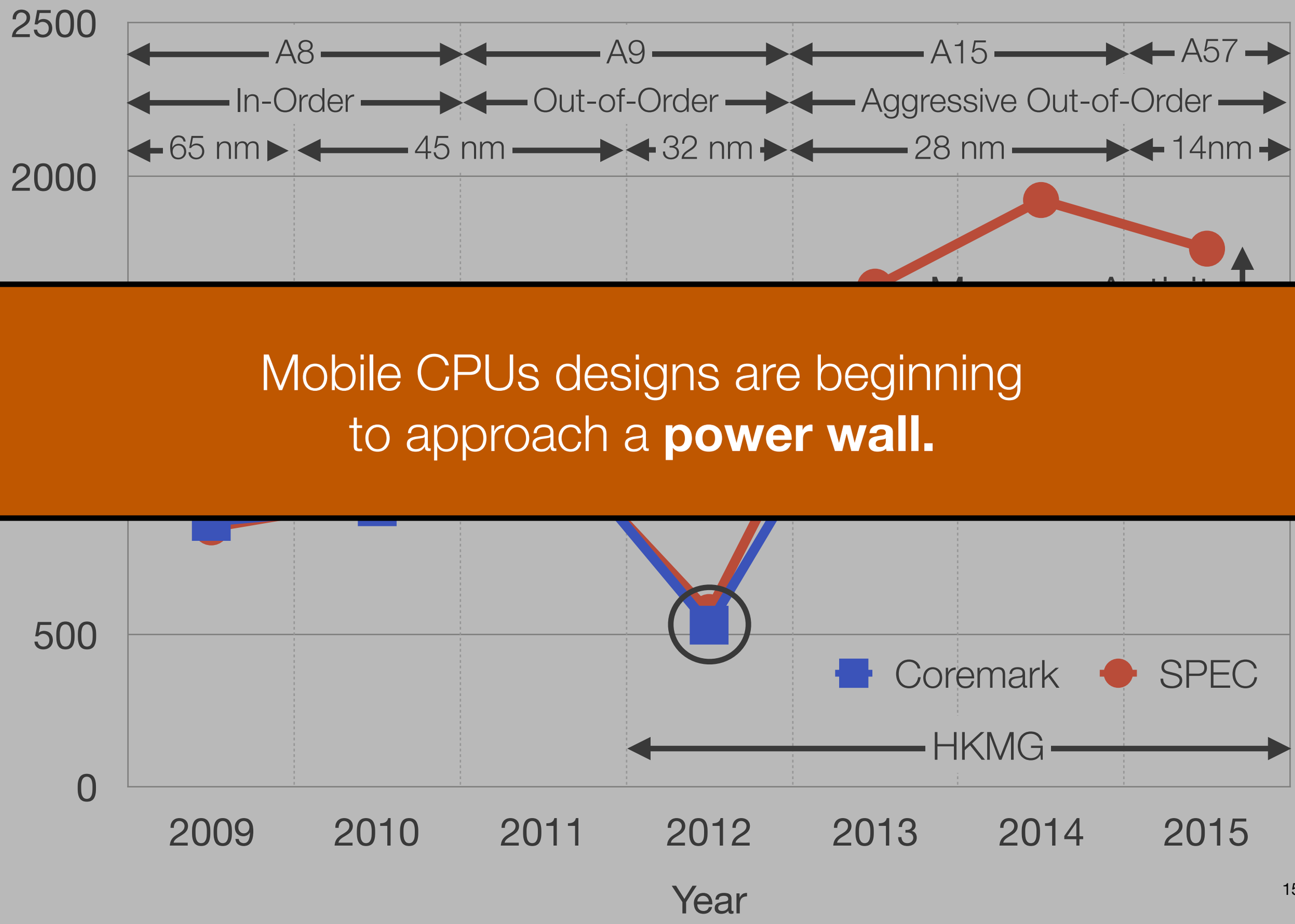
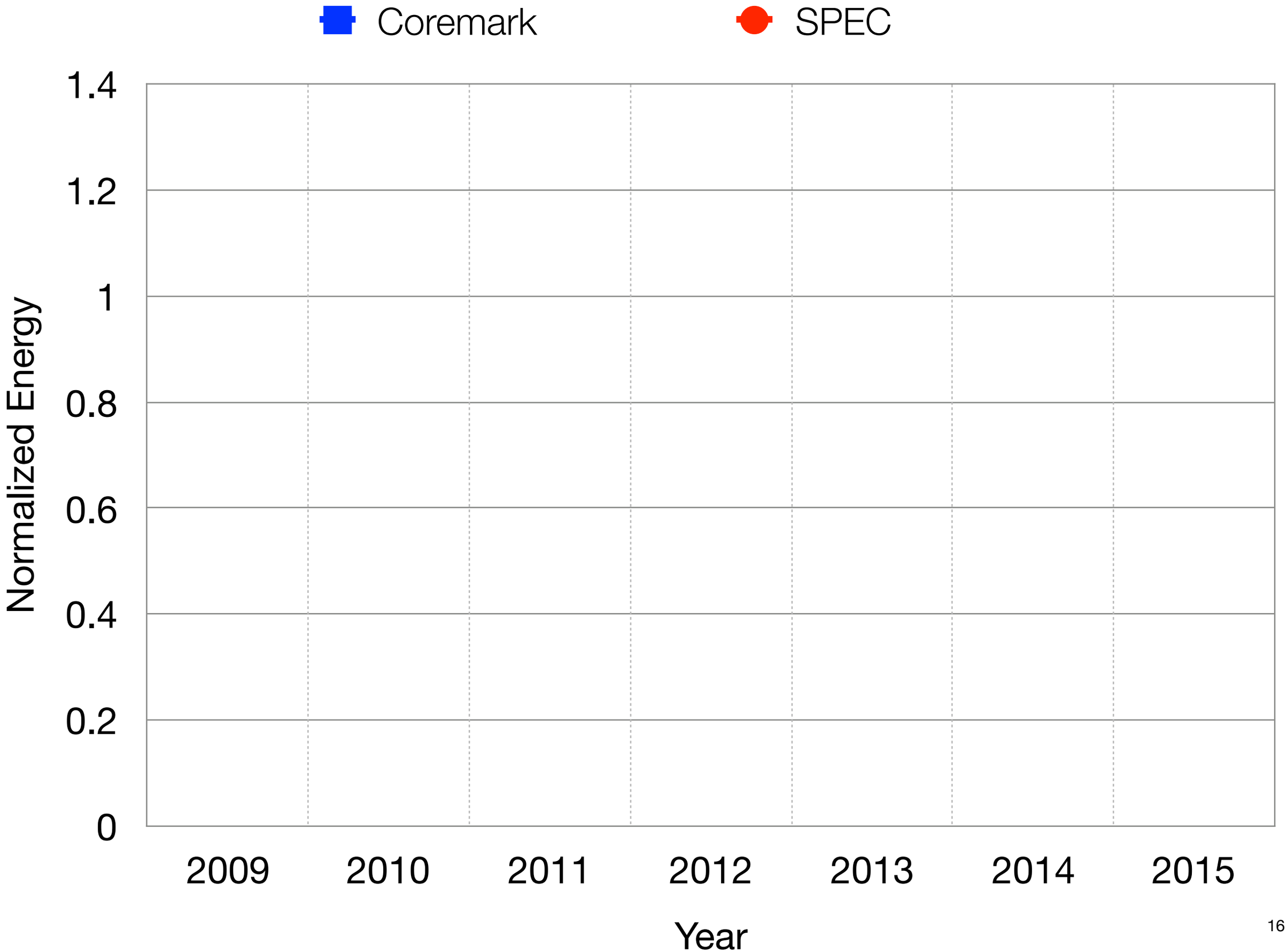


Mobile CPUs designs are beginning to approach a **power wall.**


Coremark
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Normalized Energy
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2013
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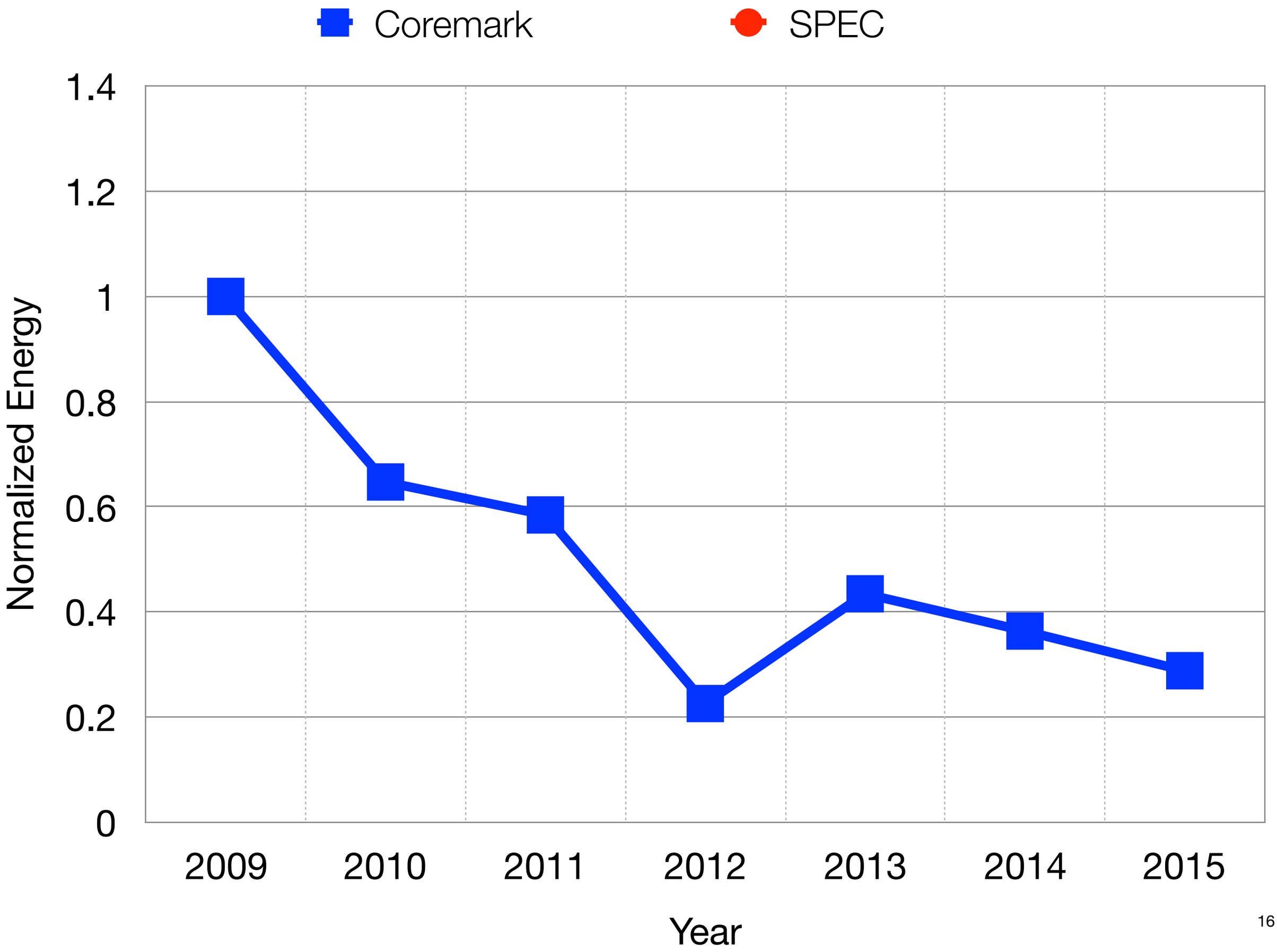
Coremark
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Normalized Energy
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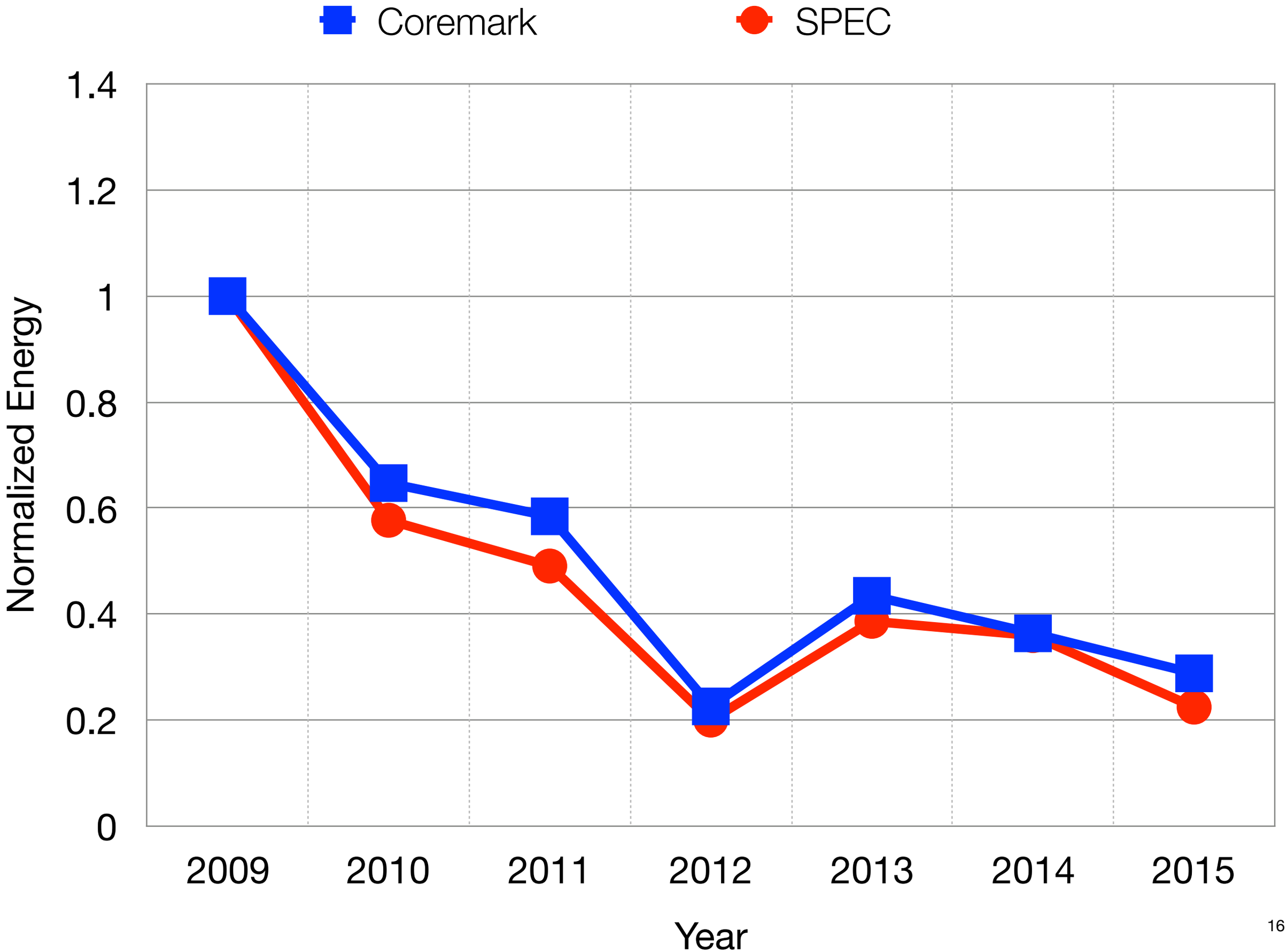
Coremark
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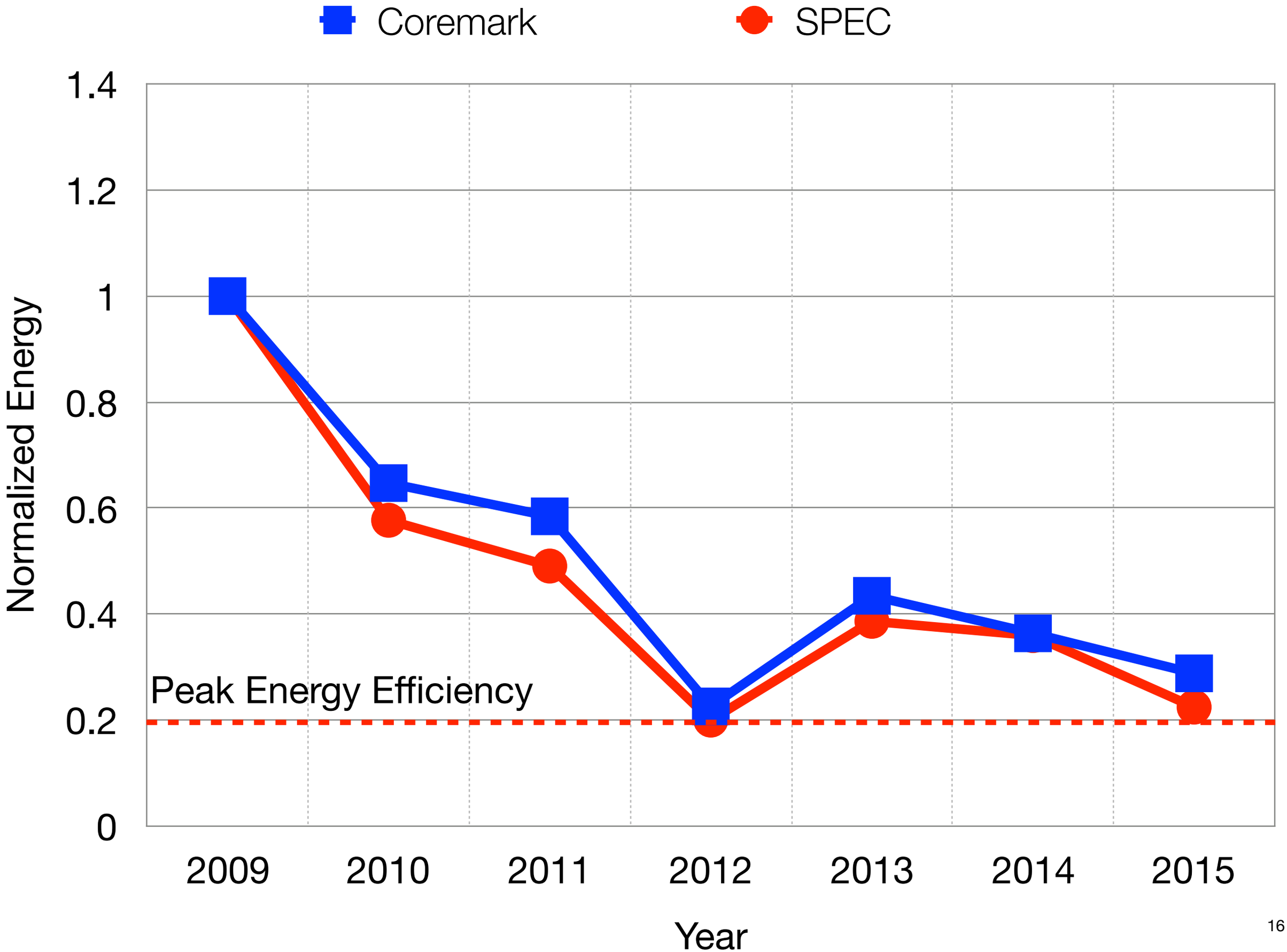
Coremark
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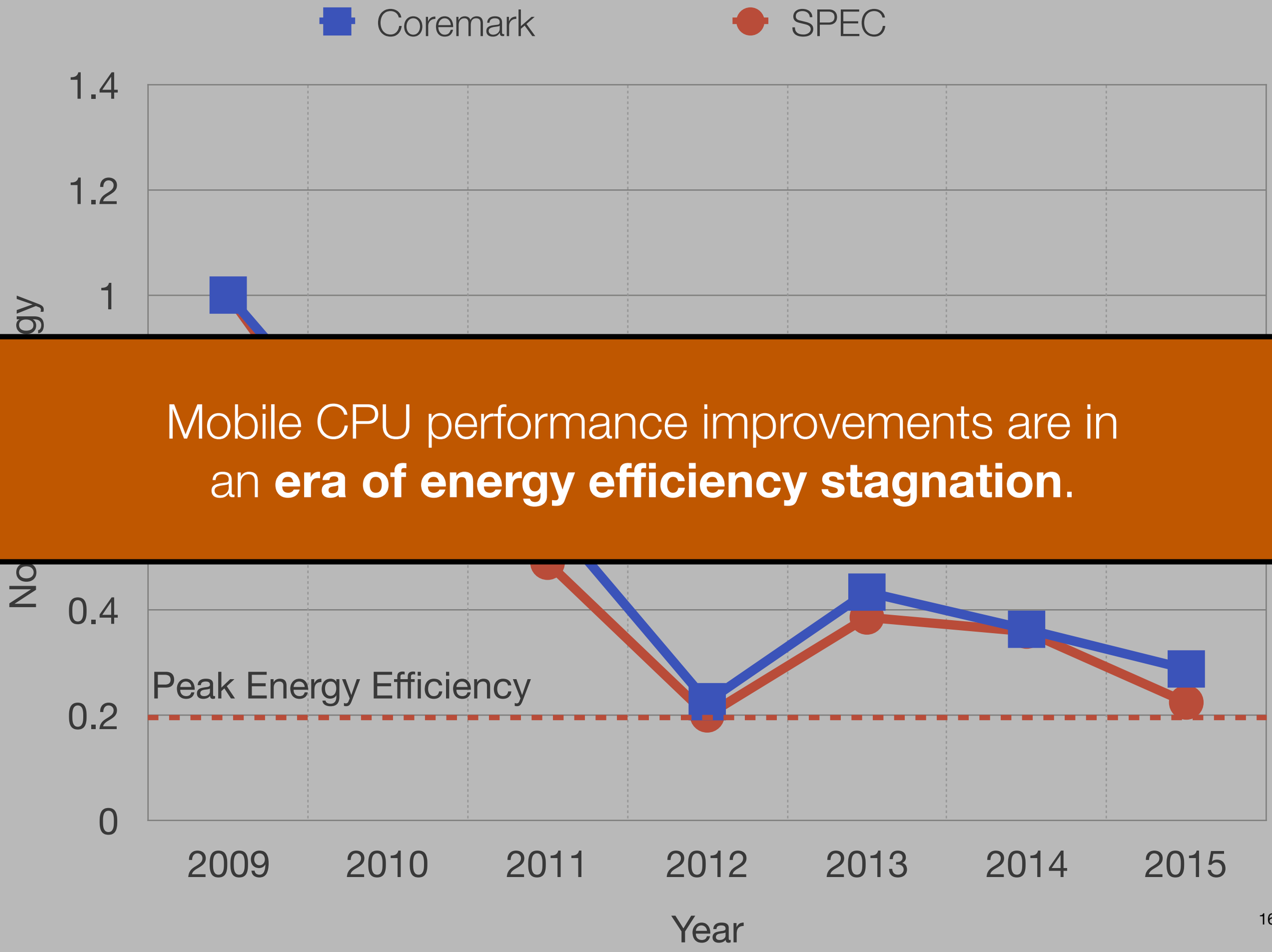
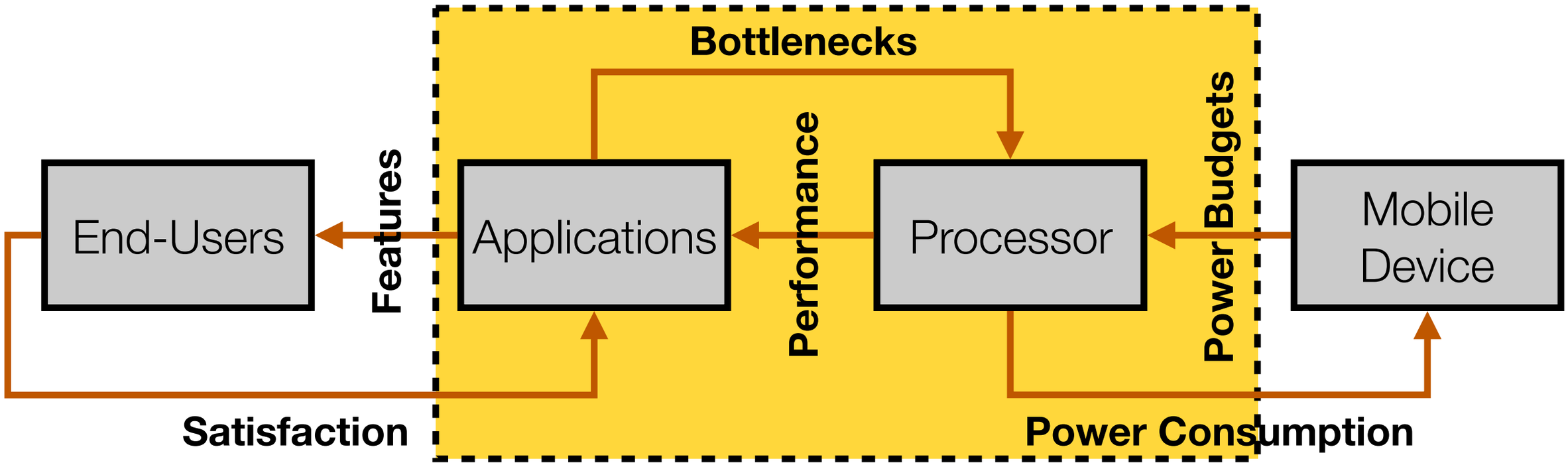


Mobile CPU performance improvements are in an **era of energy efficiency stagnation**.

Incorporating the End-User



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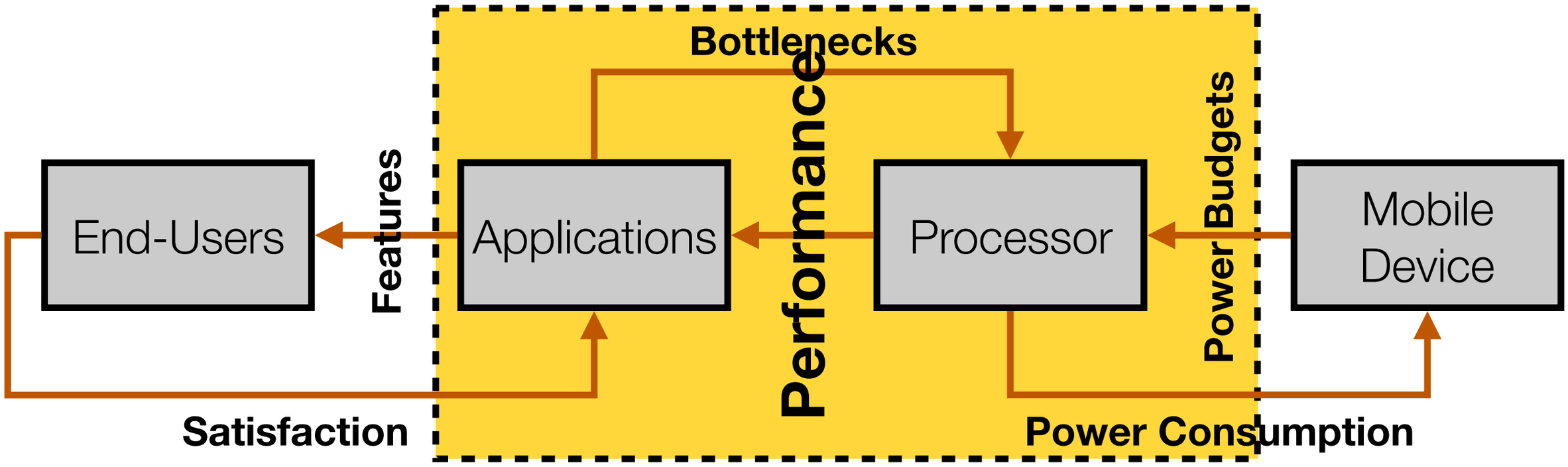

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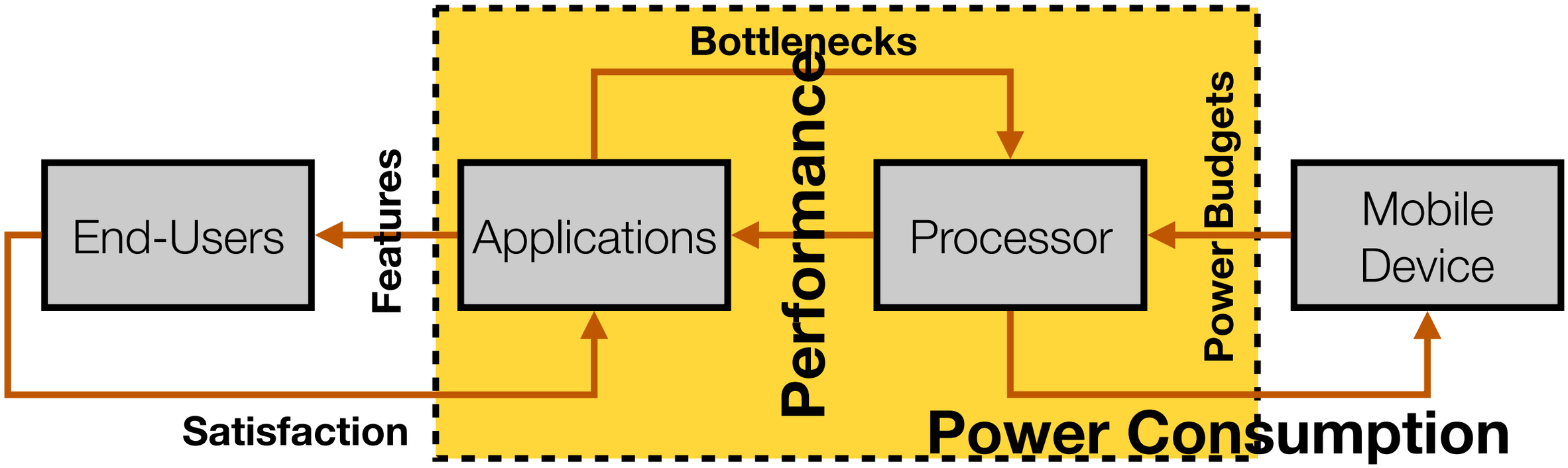

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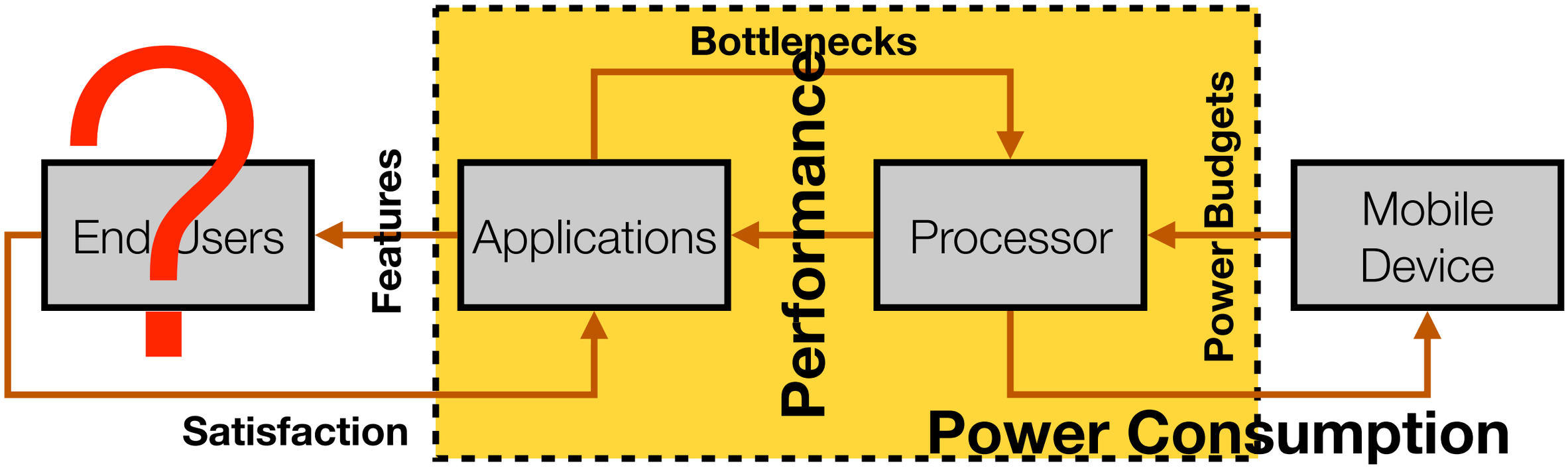

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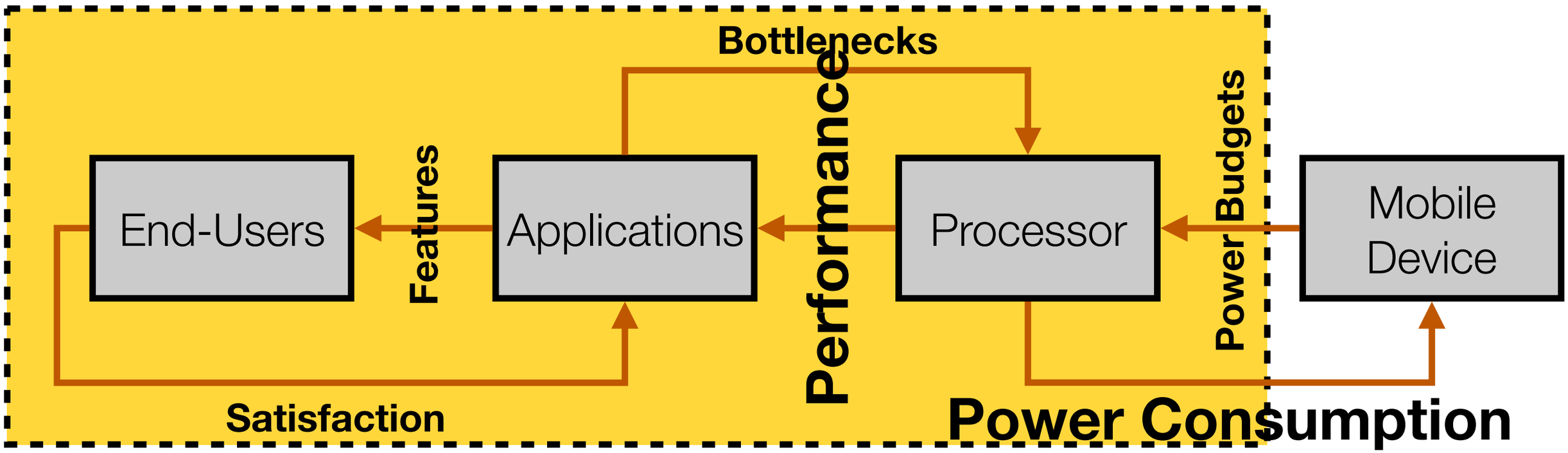

Have mobile CPU advancements improved end-user satisfaction?

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1. Is single-core performance necessary?

Have mobile CPU advancements improved end-user satisfaction?

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2. Is multi-core performance necessary?

Have mobile CPU advancements improved end-user satisfaction?

1. Is single-core performance necessary?
2. Is multi-core performance necessary?
3. Does graphics performance matter more than CPU performance?

Studying user satisfaction requires users

Studying user satisfaction requires users ^ LOTS

Leveraging the Crowd to Achieve Scale

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How It Works

Choose the Right Tool

Survey Design

1. Thank you for participating in our smartphone user experience study. The clip shown above is an application usage scenario recorded on an Android smartphone. As a user of the application, how satisfied are you with the smartphone's performance (i.e., application responsiveness and fluidness)?

- ◯ 5 - Very Satisfied
- ◯ 4 - Satisfied
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Emulating the Mobile CPU Evolution

2009 2010 2011 2012 2013 2014

Year

Emulating the Mobile CPU Evolution

Emulating the Mobile CPU Evolution

D S

2009 2010 2011 2012 2013 2014

Year

Emulating the Mobile CPU Evolution

D S N

2009 2010 2011 2012 2013 2014

Year

Emulating the Mobile CPU Evolution

D S N S3

2009 2010 2011 2012 2013 2014

Year

Emulating the Mobile CPU Evolution

D S N S3 S4

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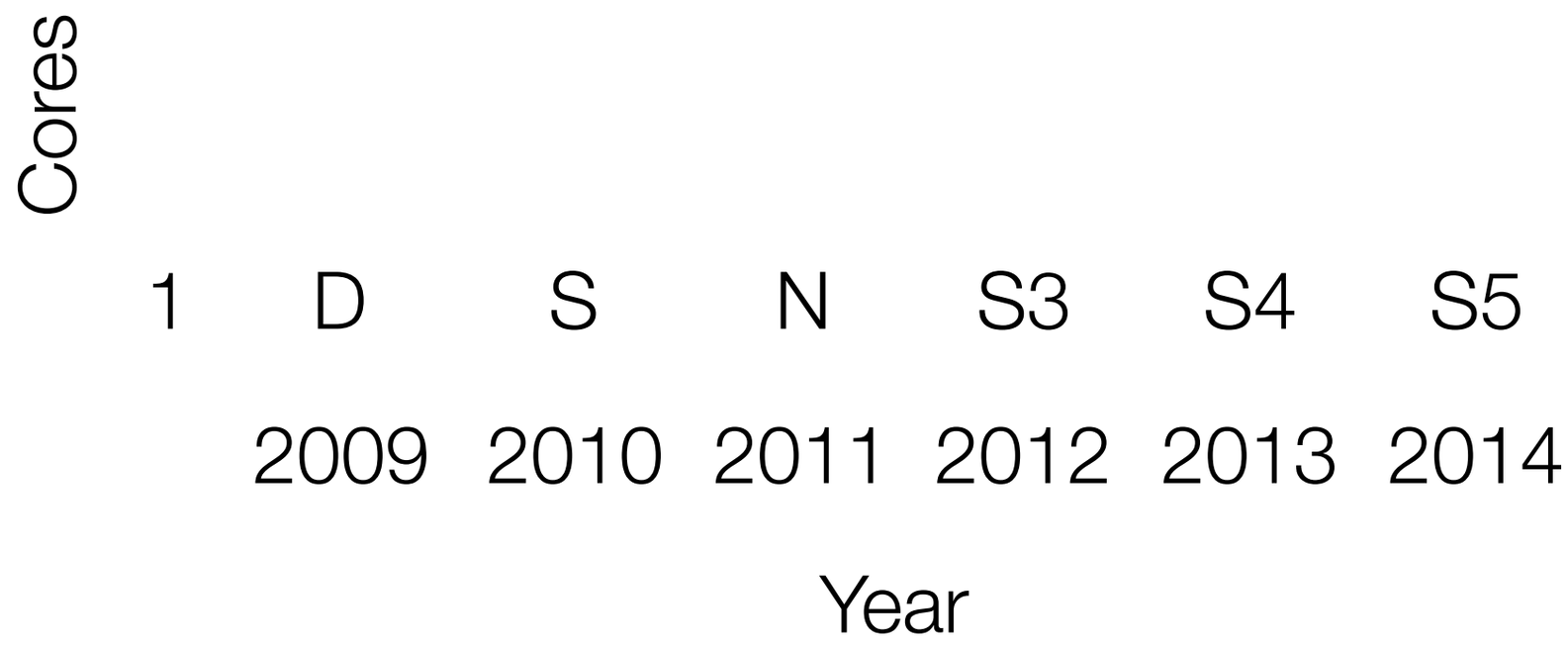
Year

Emulating the Mobile CPU Evolution

D	S	N	S3	S4	S5
2009	2010	2011	2012	2013	2014

Year

Emulating the Mobile CPU Evolution



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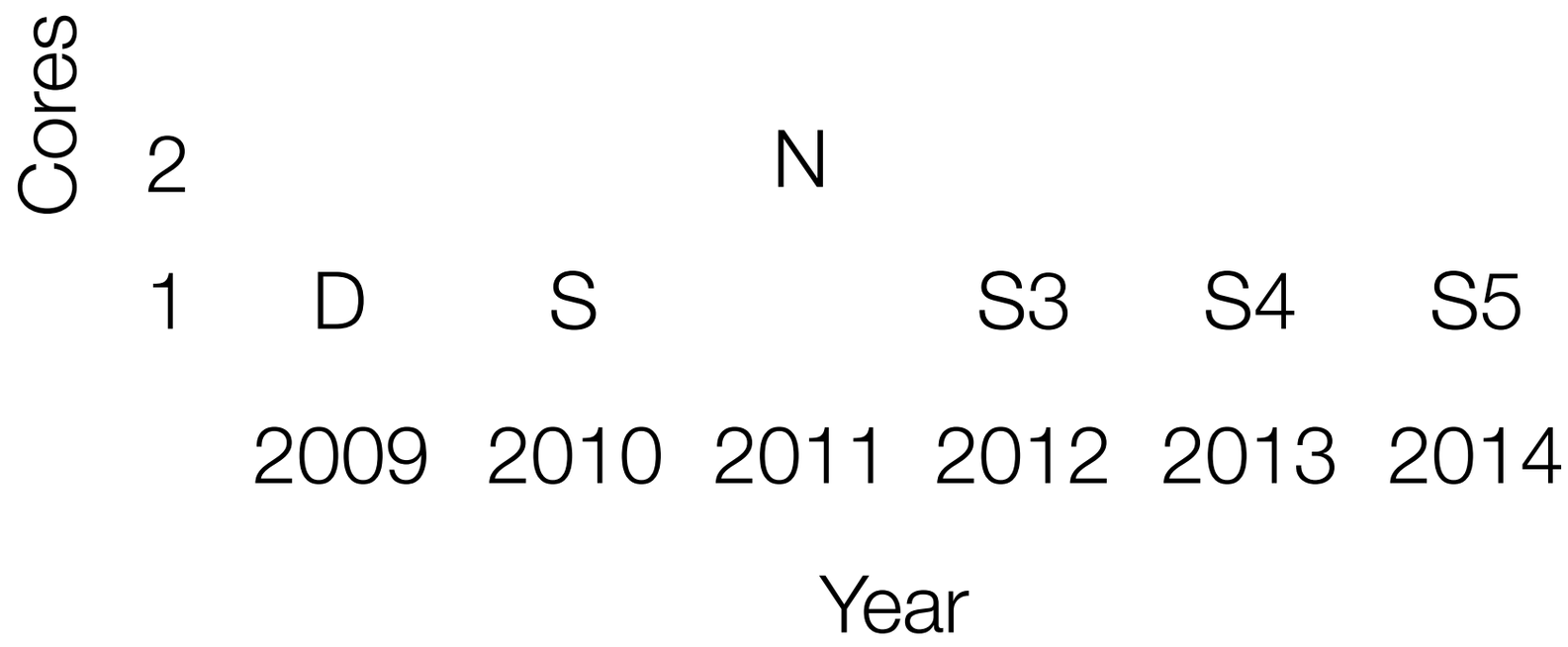

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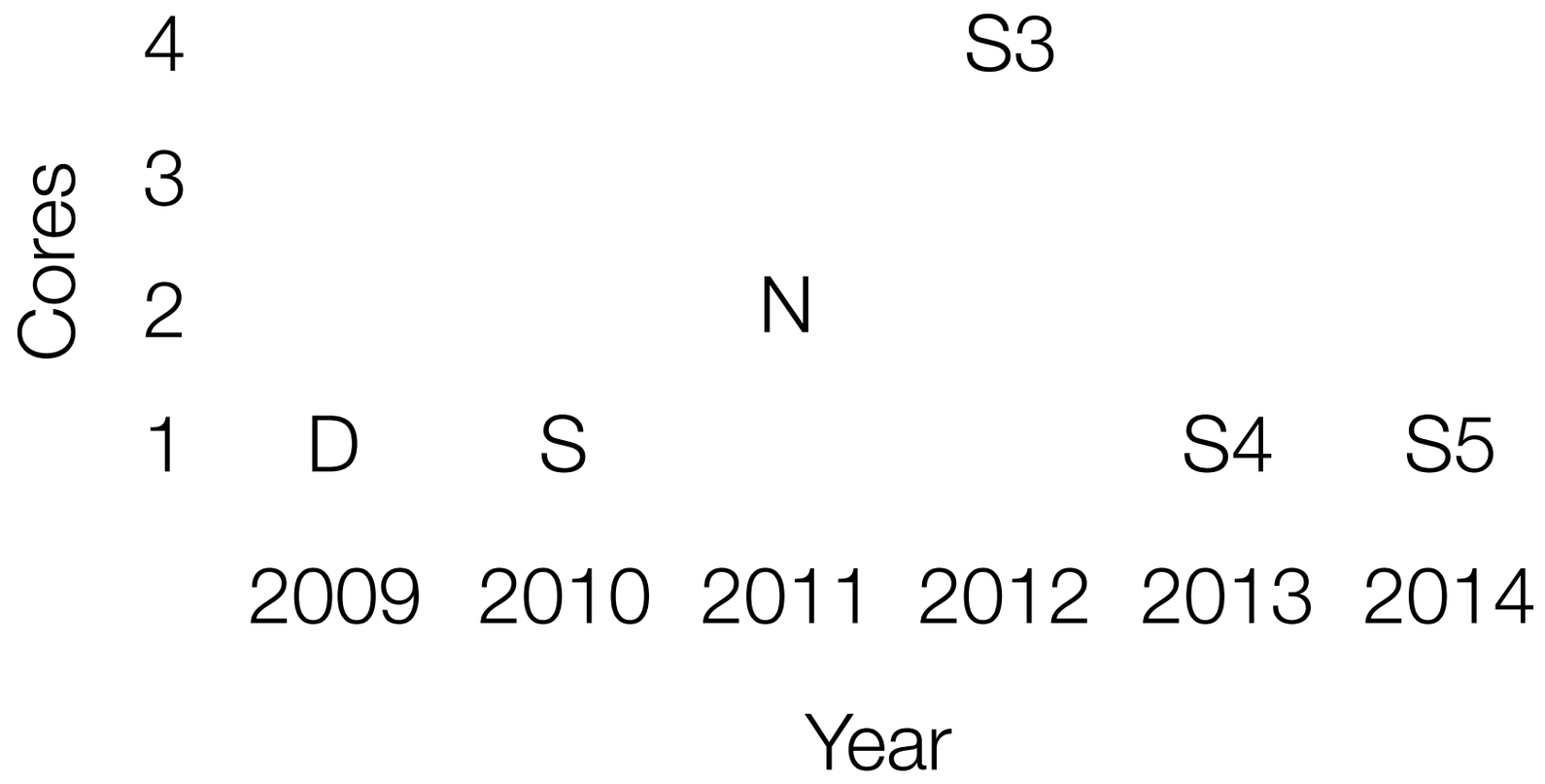

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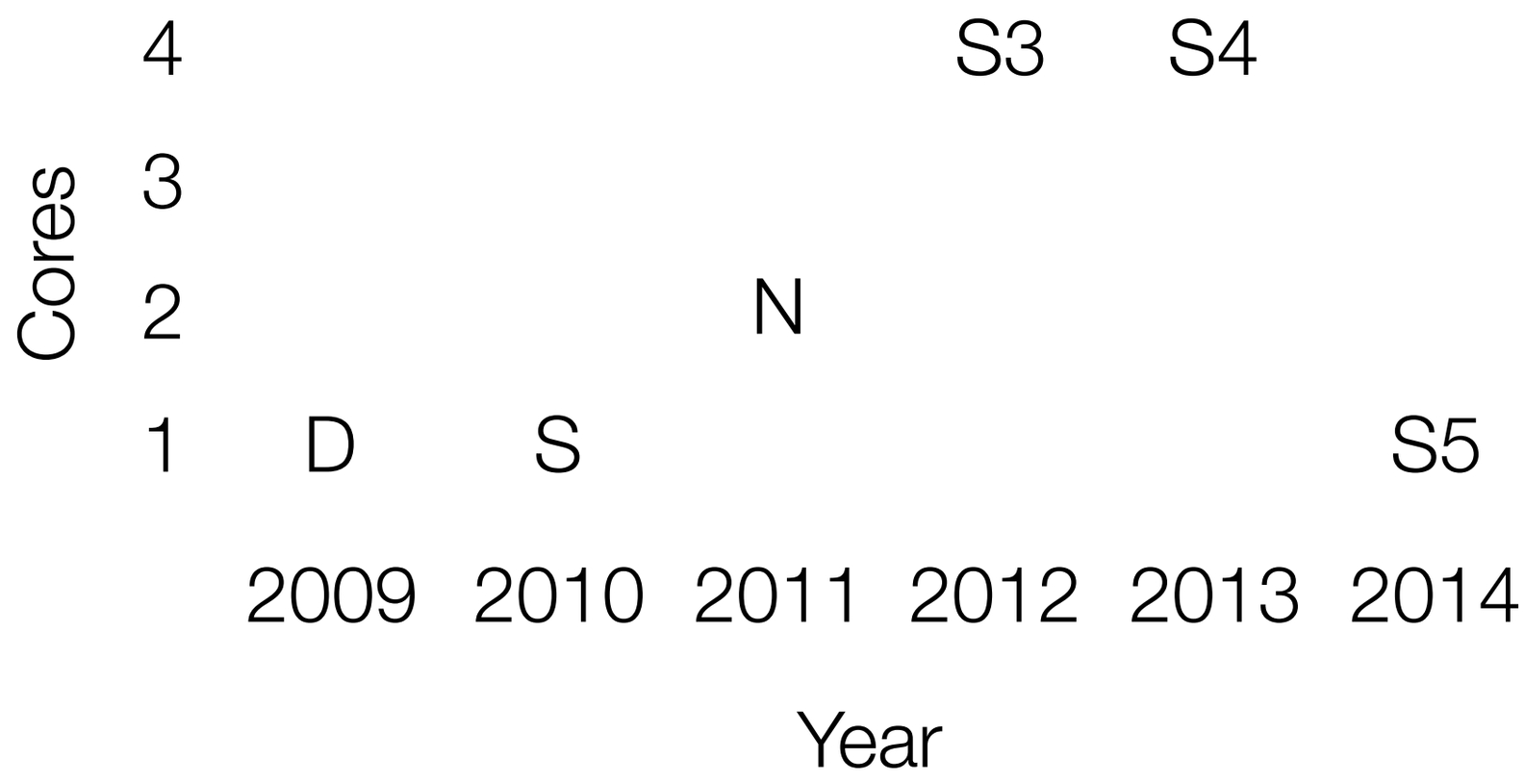

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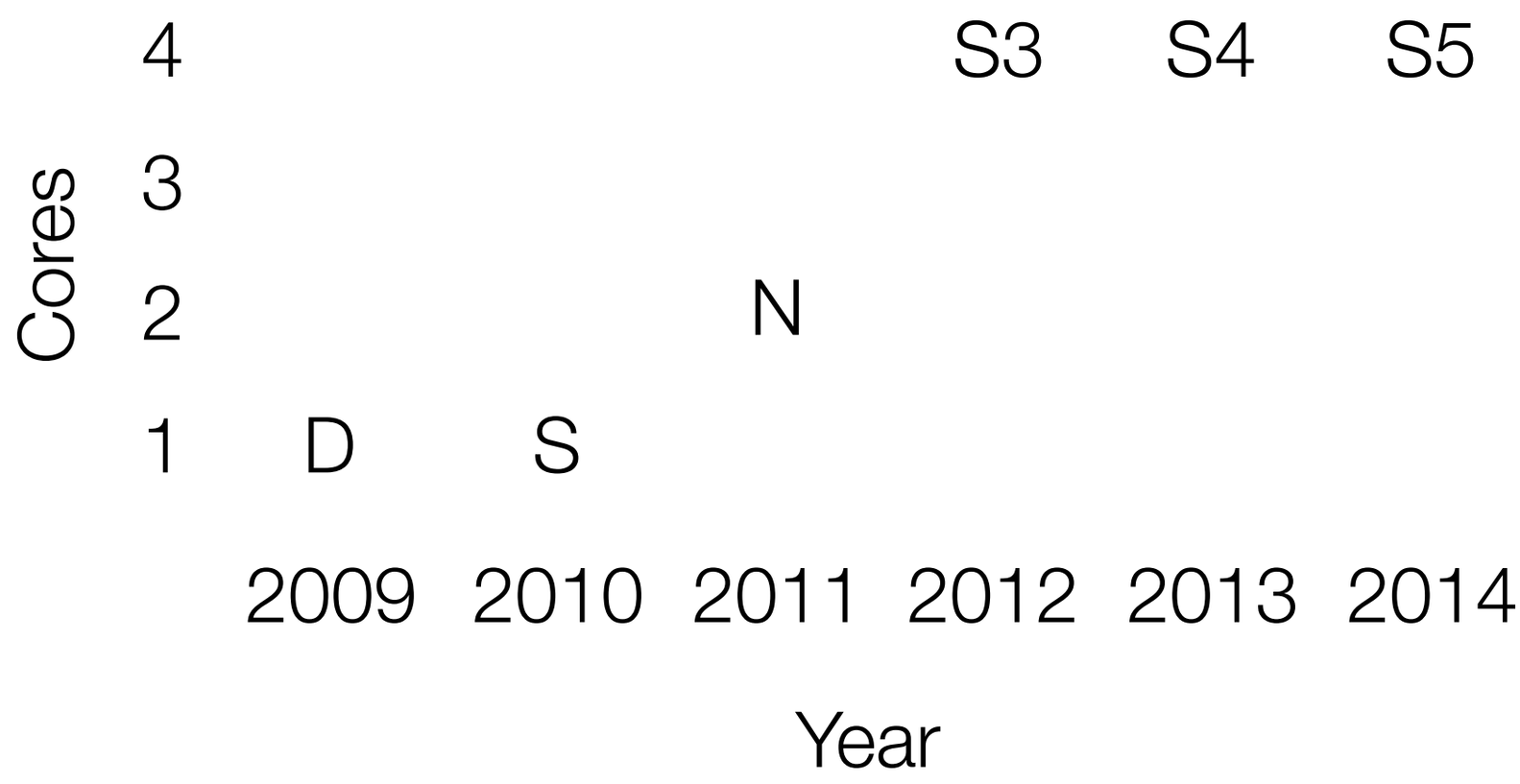

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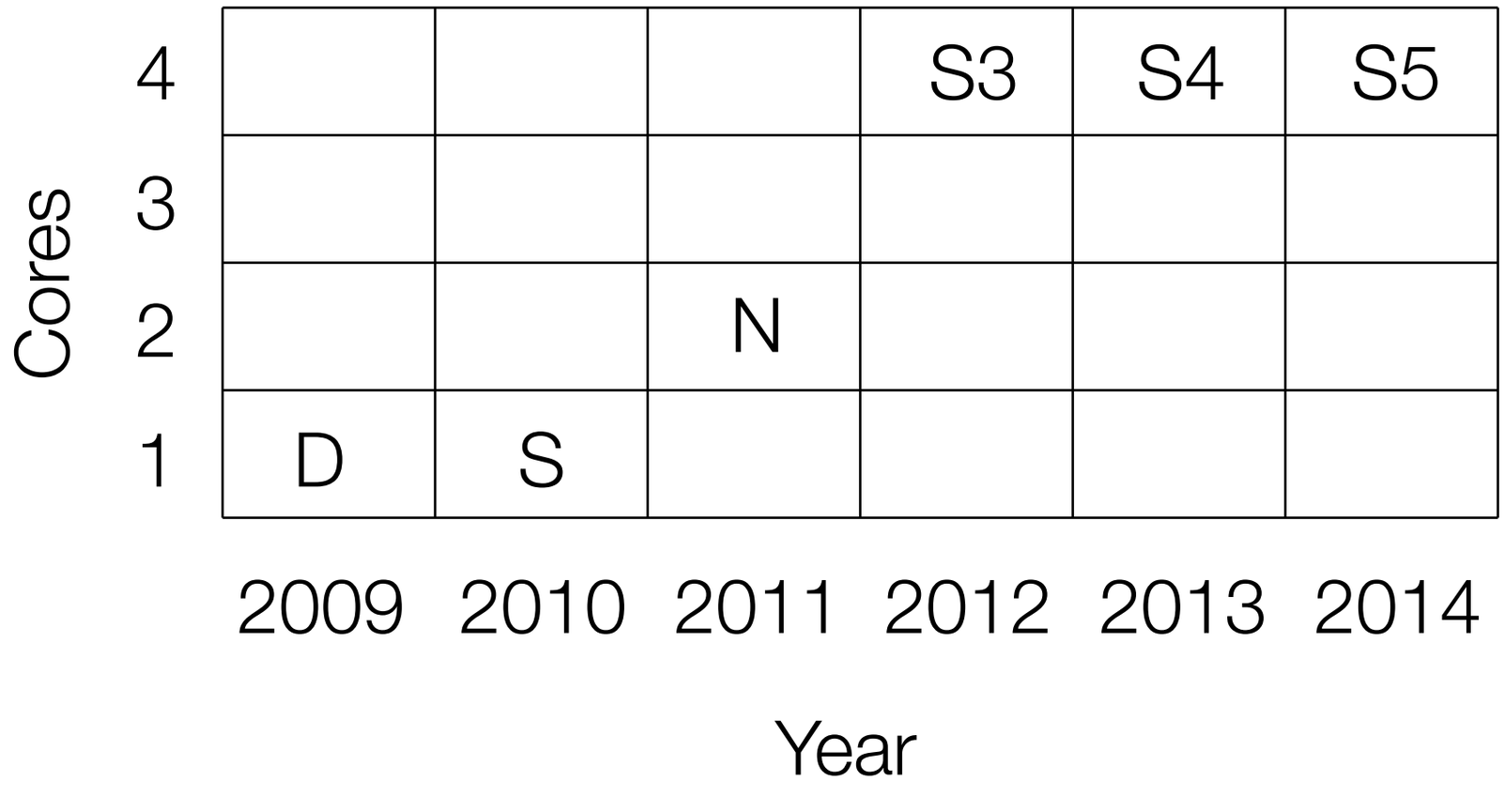

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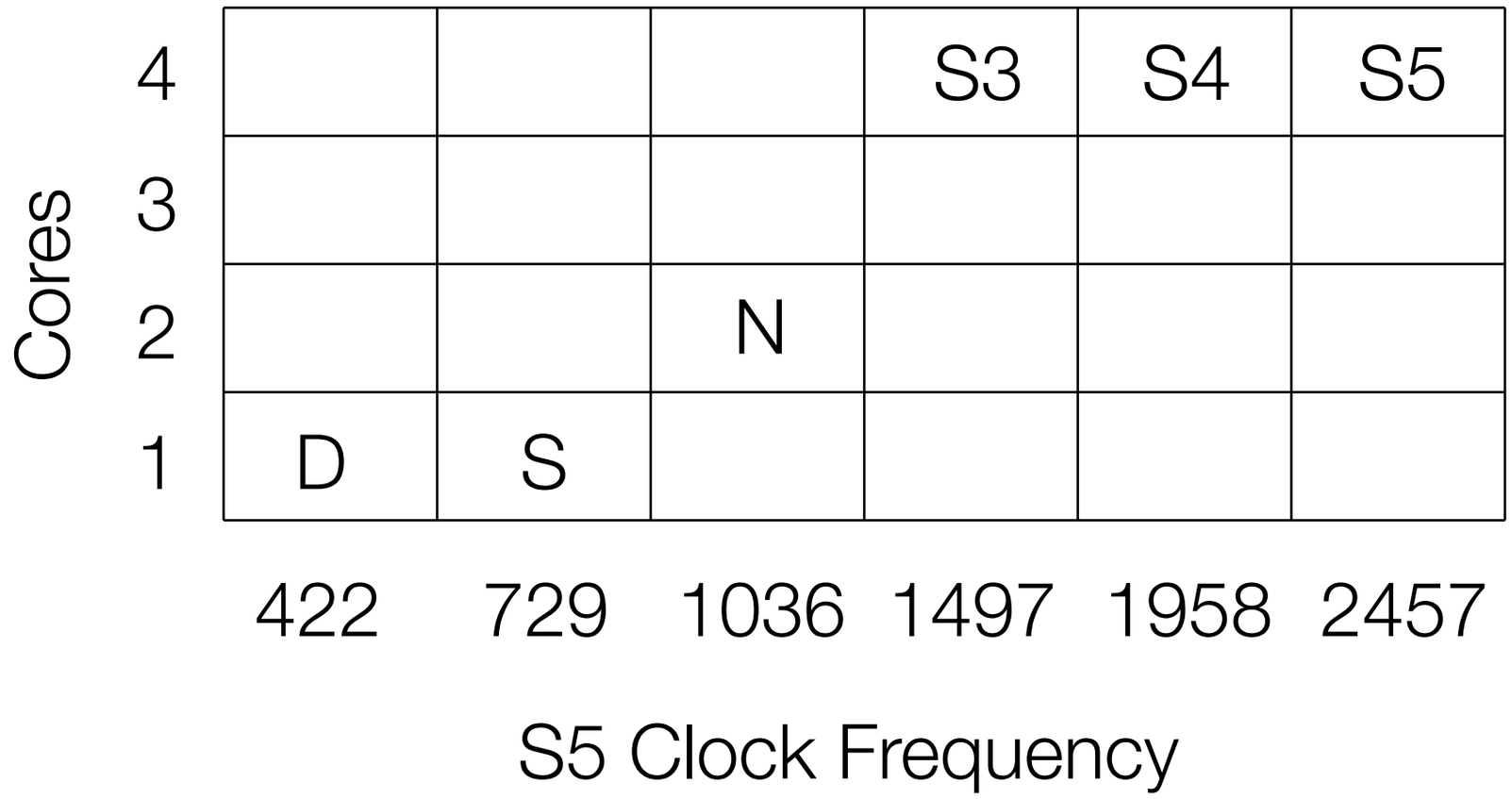

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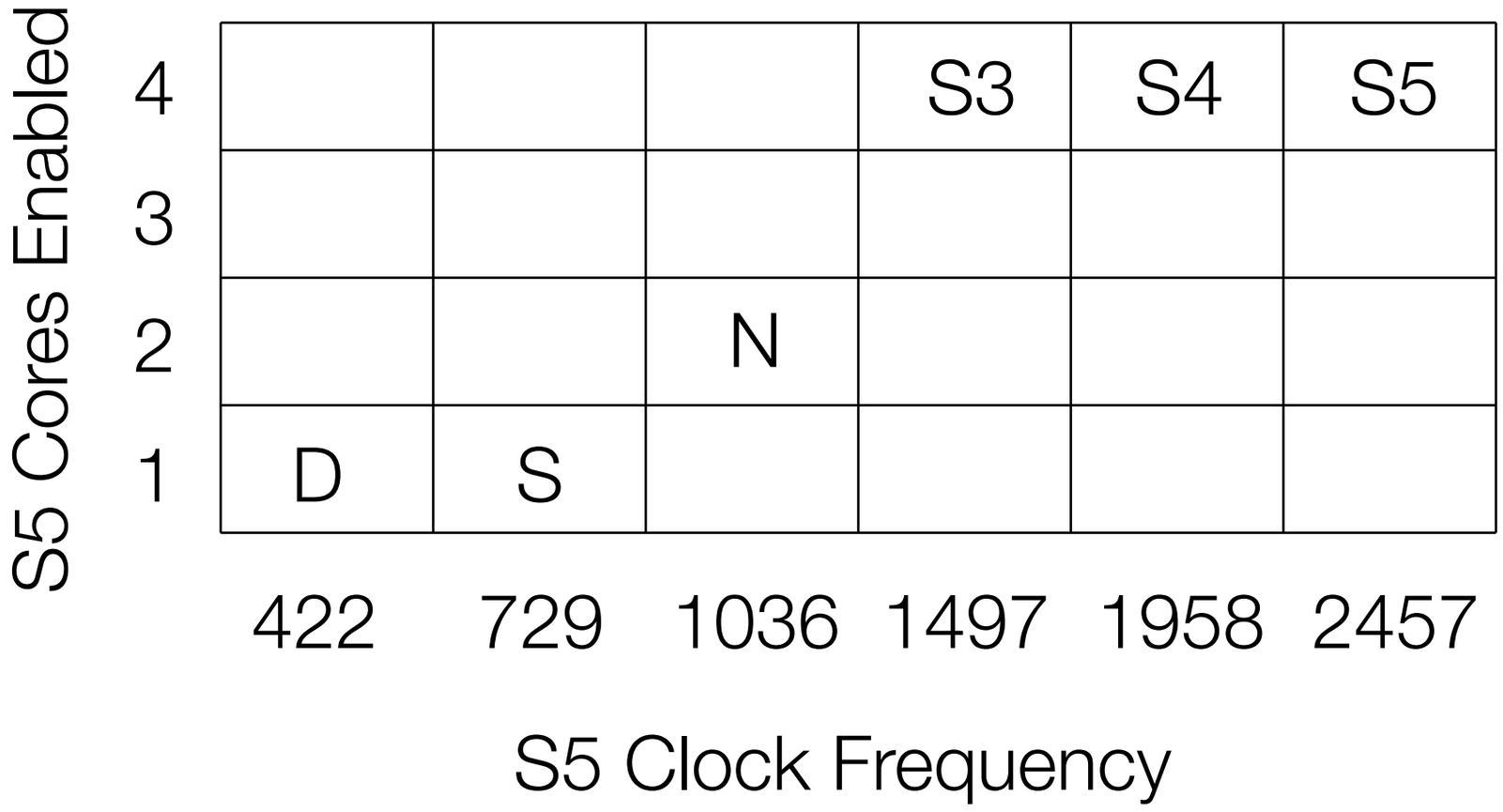

Putting the Pieces Together

Record User

Parametrized Replay

Post Survey

Crowdsource

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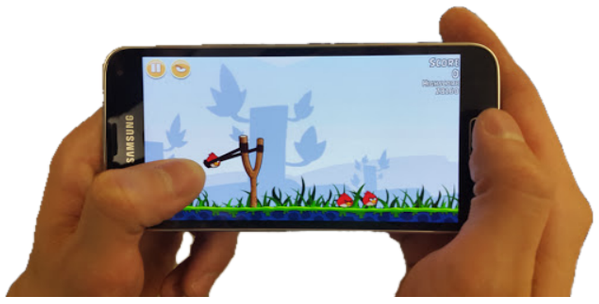
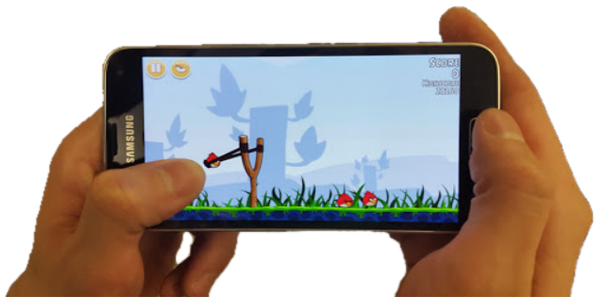


Putting the Pieces Together

Record User Parametrized Replay Post Survey Crowdsource



CPU Frequency CPU Cores GPU Frequency

Putting the Pieces Together

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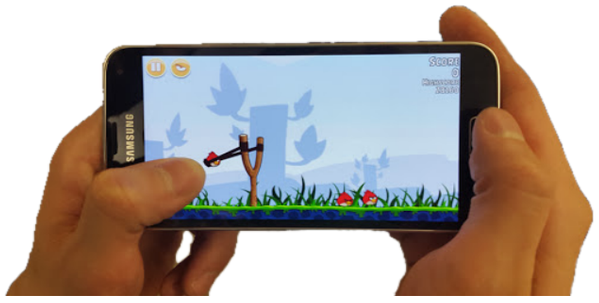
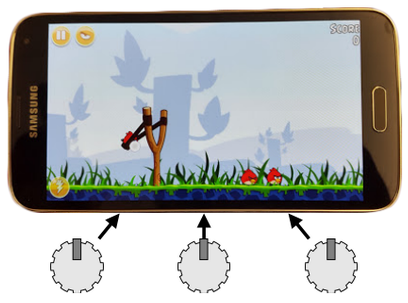


Parametrized Replay



Post Survey

Crowdsource

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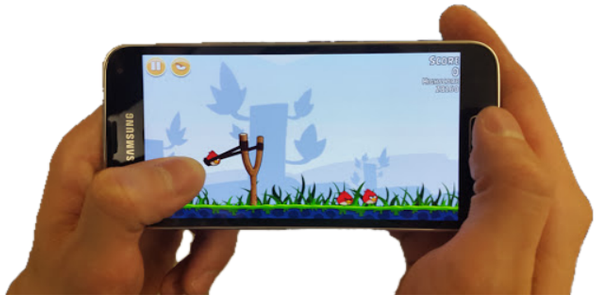
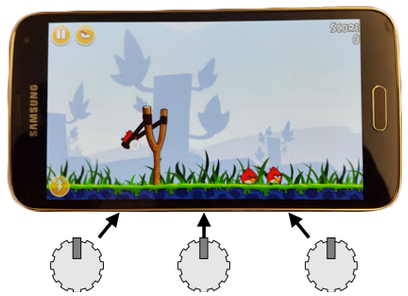


Parametrized Replay



Post Survey

1. Thank you for participating in our smartphone user experience study. The clip shown above is an application usage scenario recorded on an Android smartphone. As a user of the application, how satisfied are you with the smartphone's performance (i.e., application responsiveness and fluidness)?

- ◯ 5 - Very Satisfied
- ◯ 4 - Satisfied
- ◯ 3 - Neutral
- ◯ 2 - Dissatisfied
- ◯ 1 - Very Dissatisfied

Crowdsource

Putting the Pieces Together

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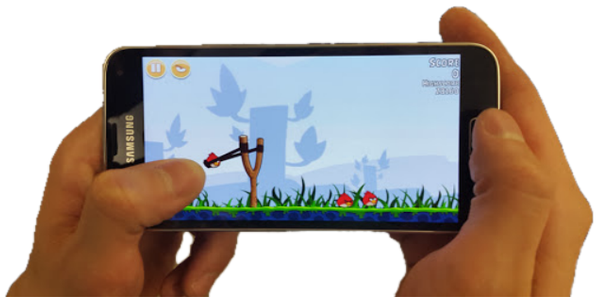

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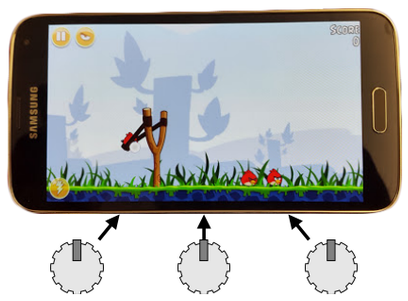

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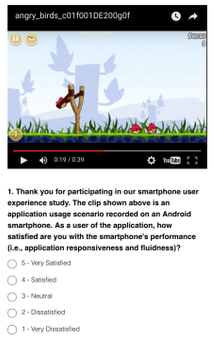

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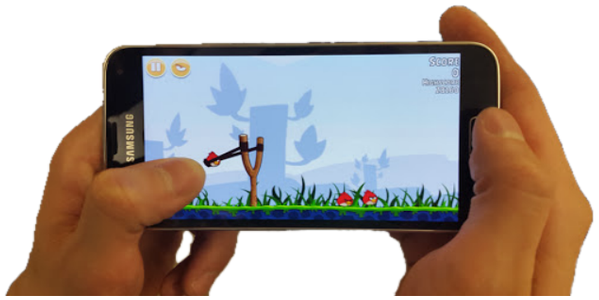

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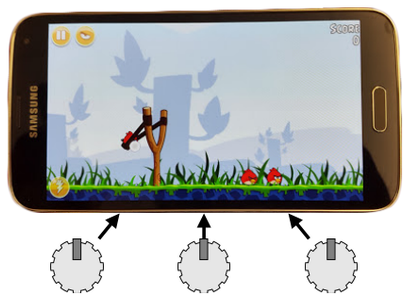

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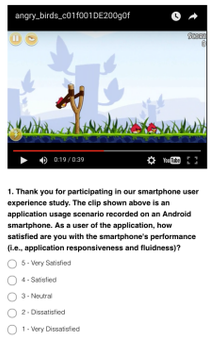

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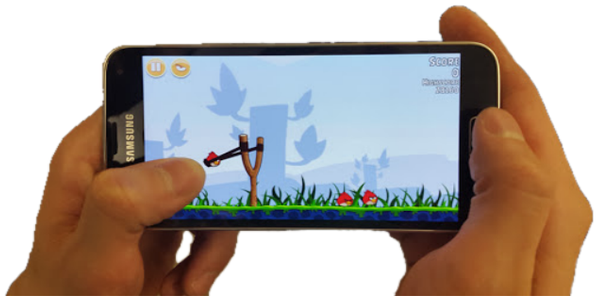

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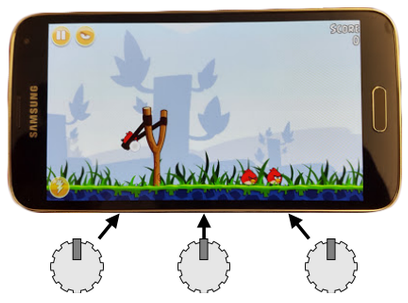

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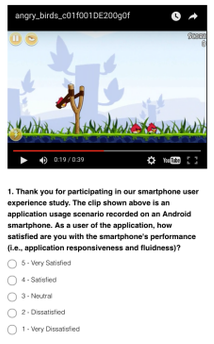

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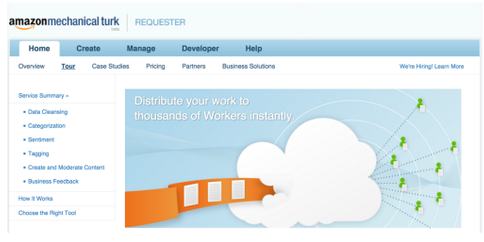

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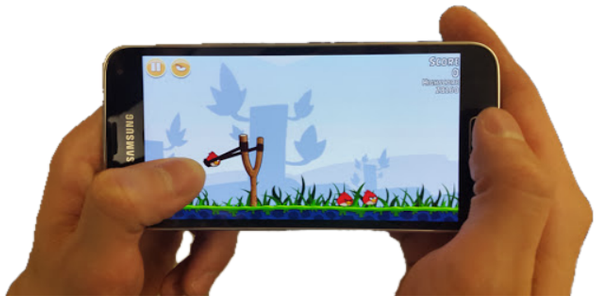

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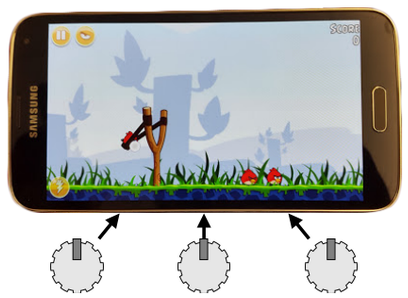

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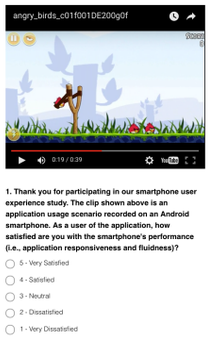

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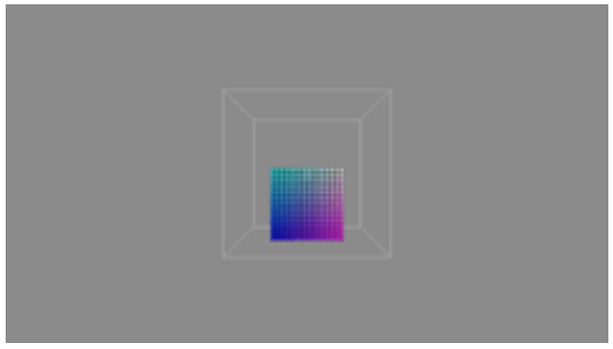
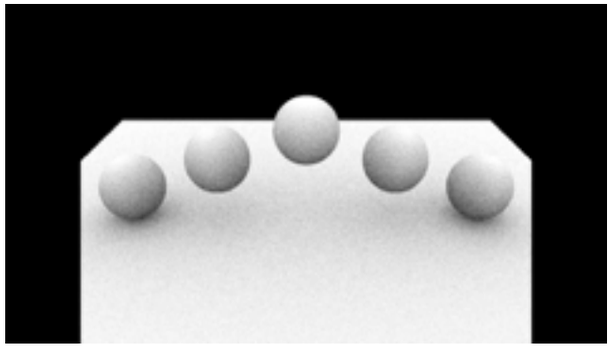
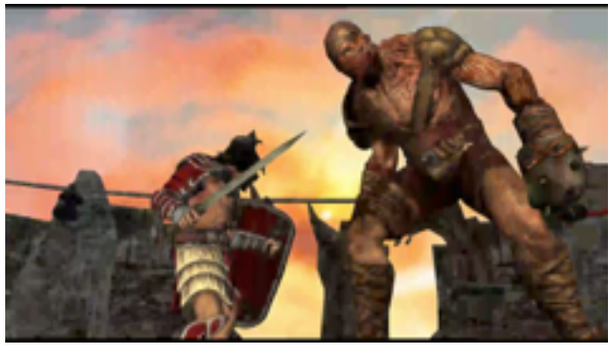
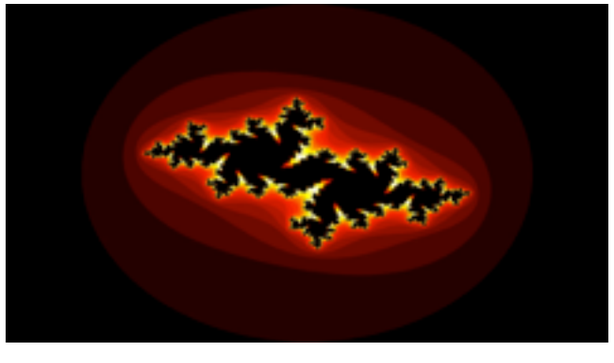
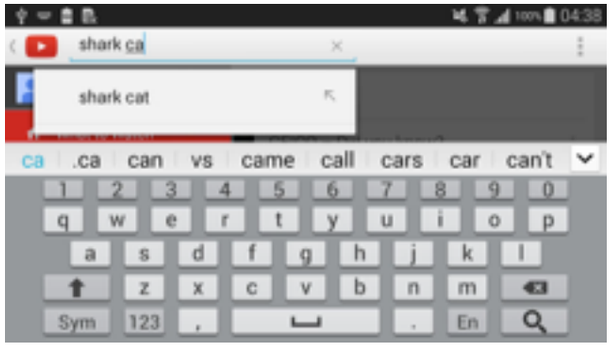


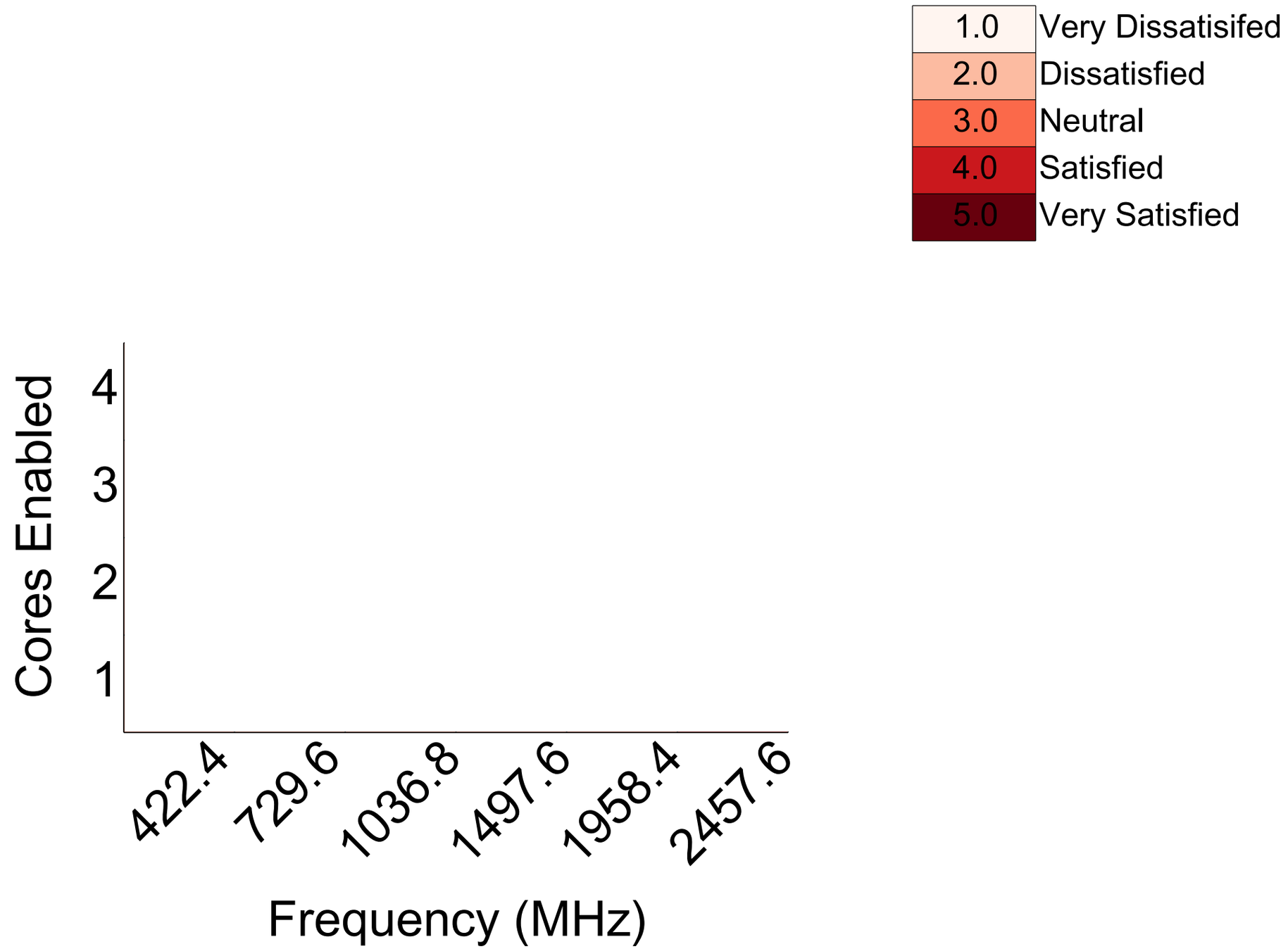








Do we need single-core performance?



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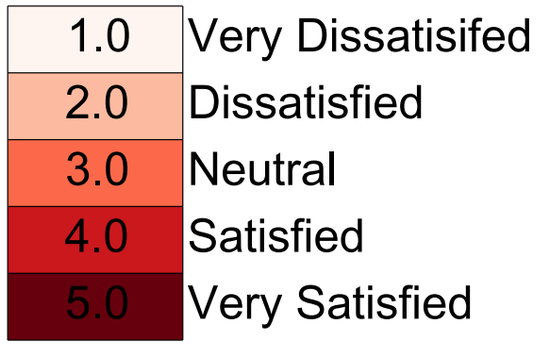

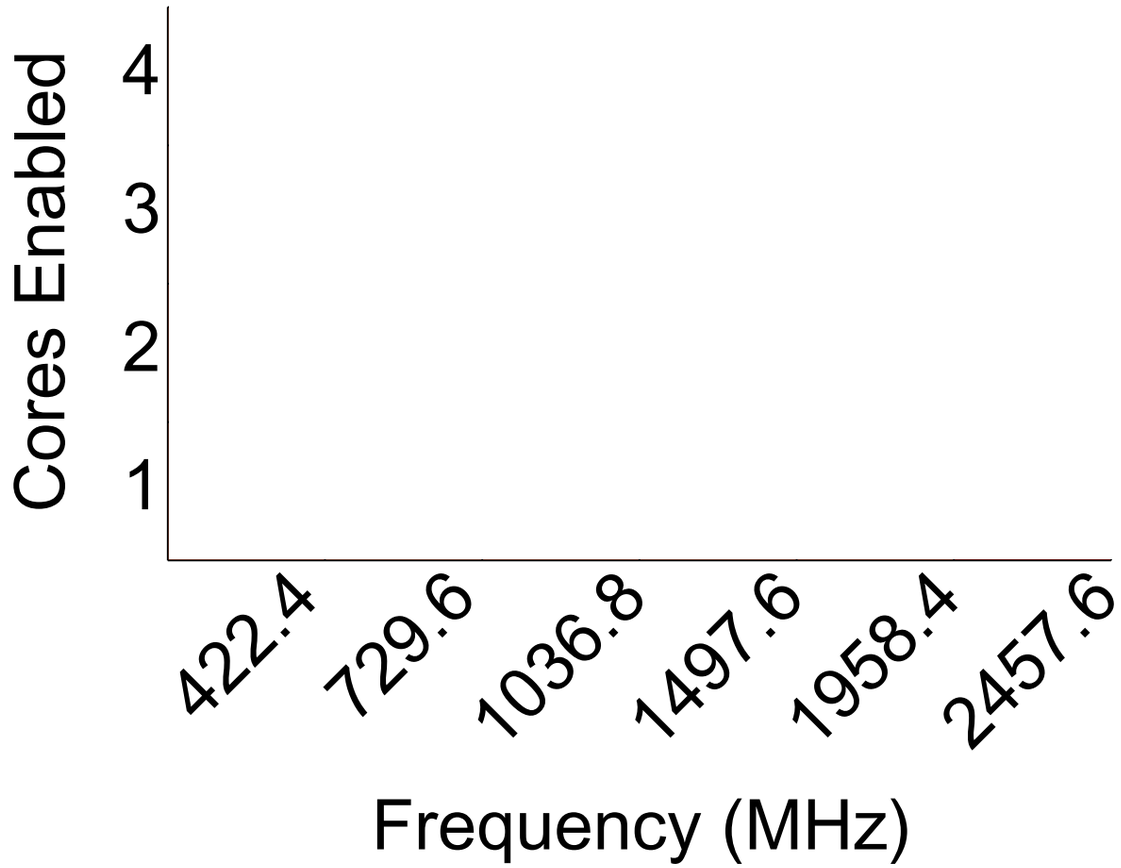

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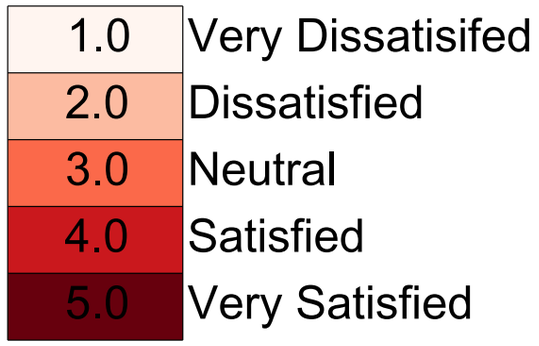

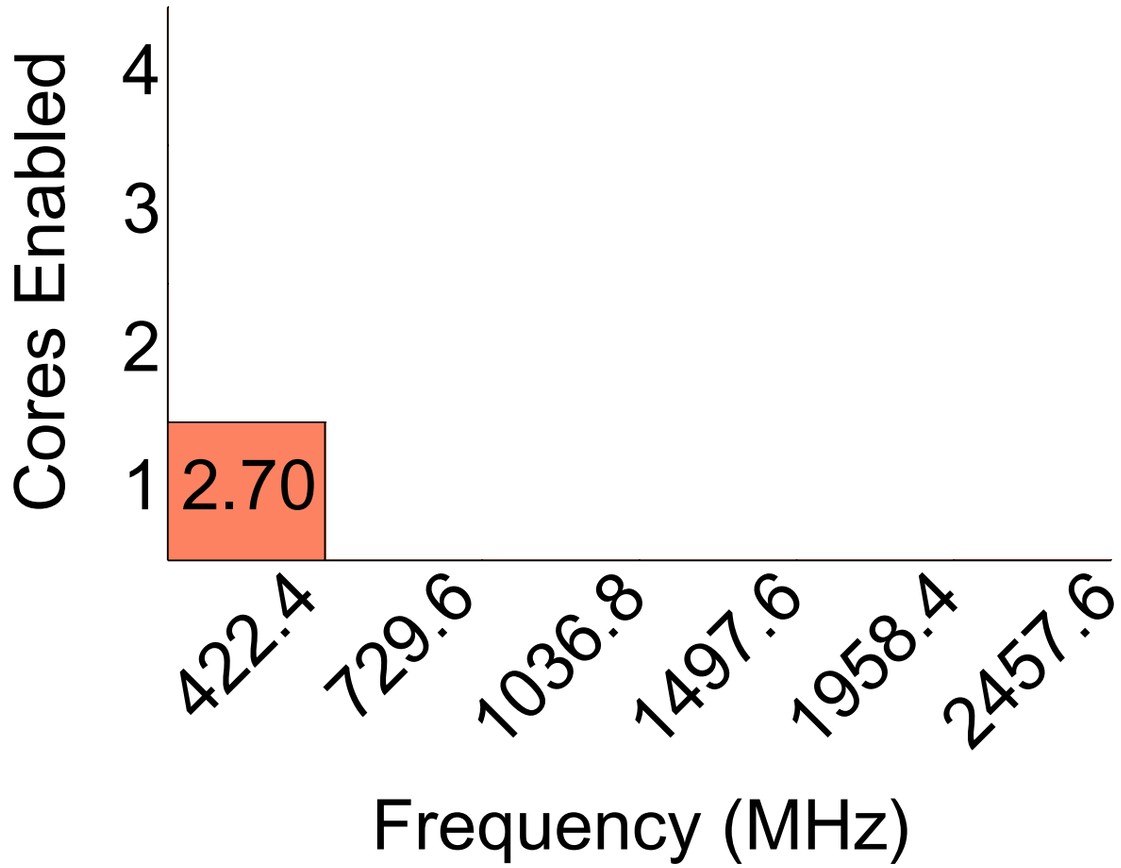

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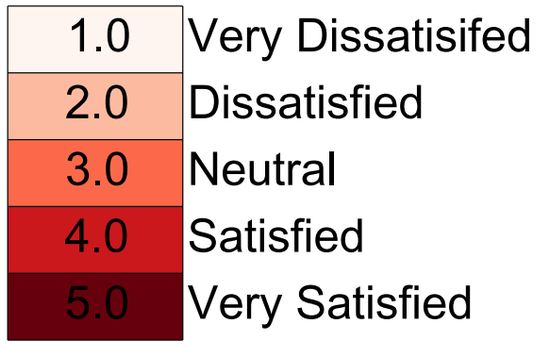

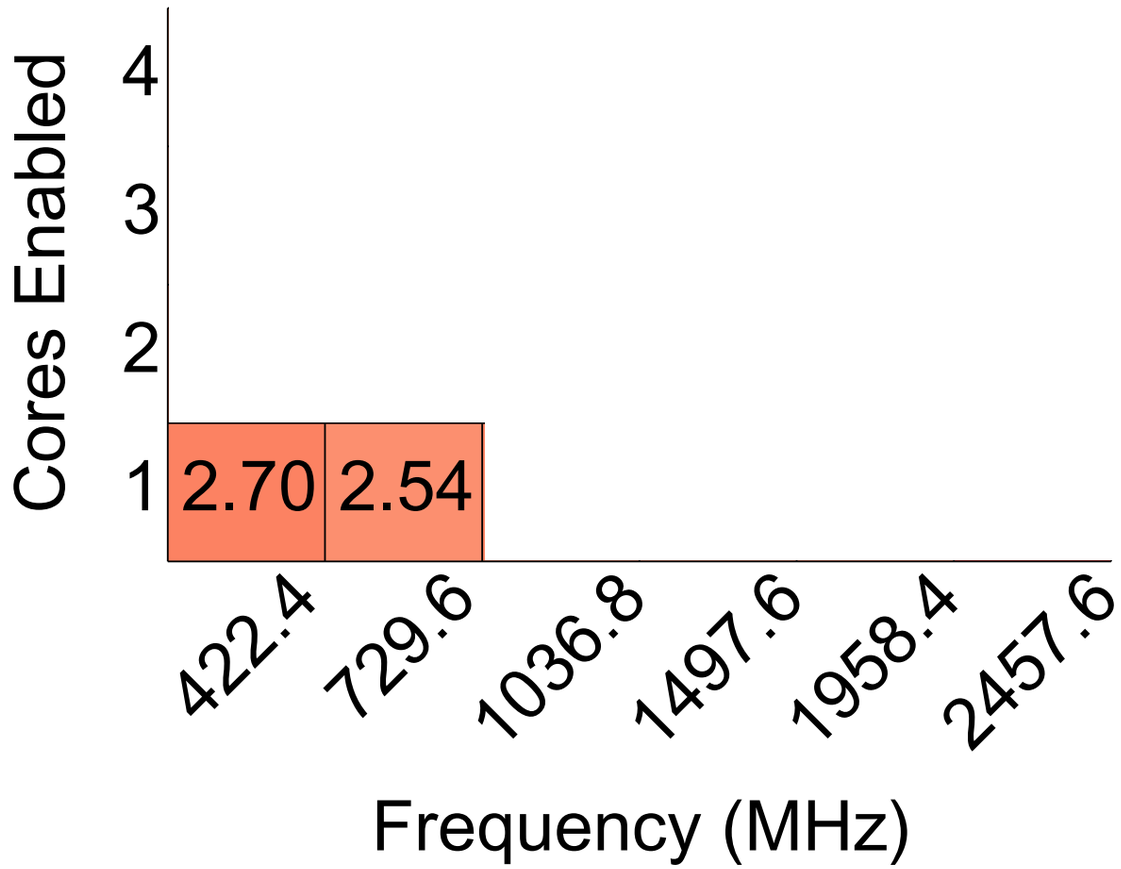

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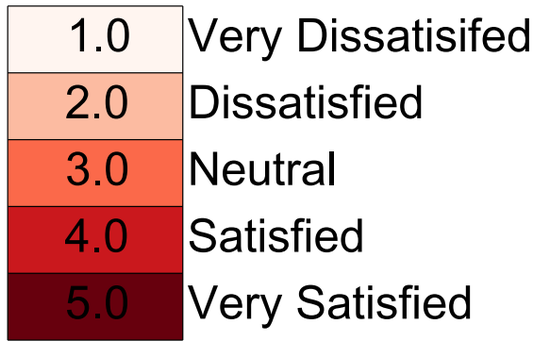

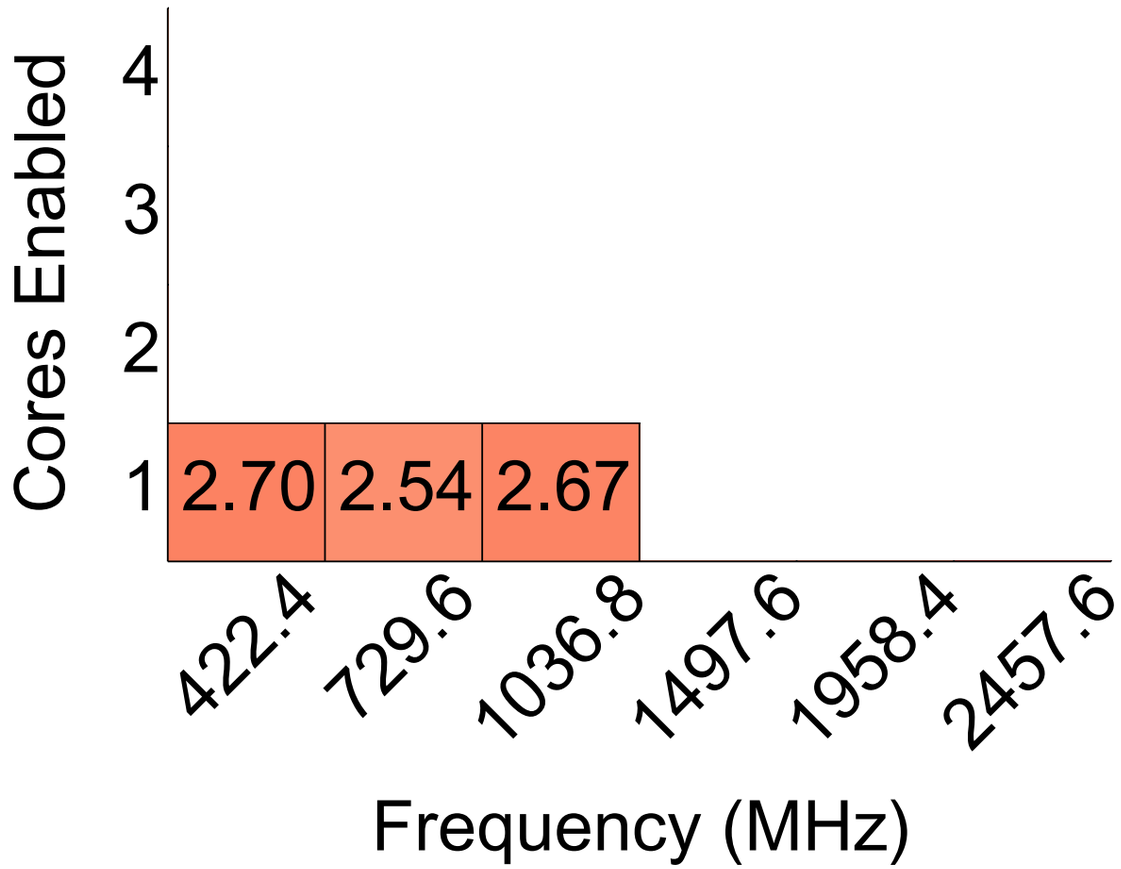

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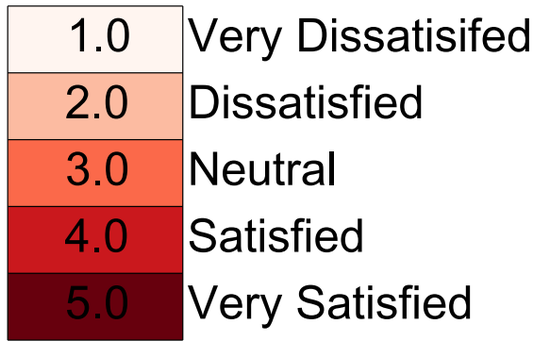

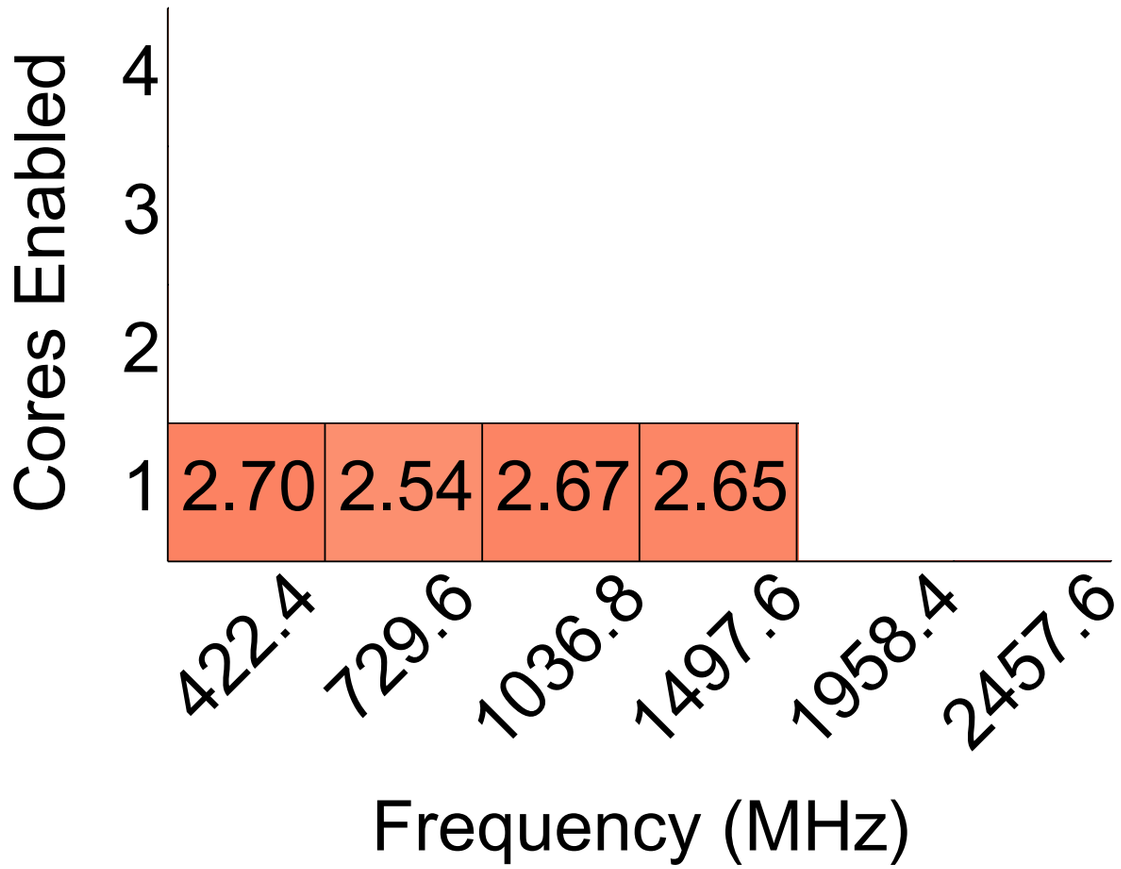

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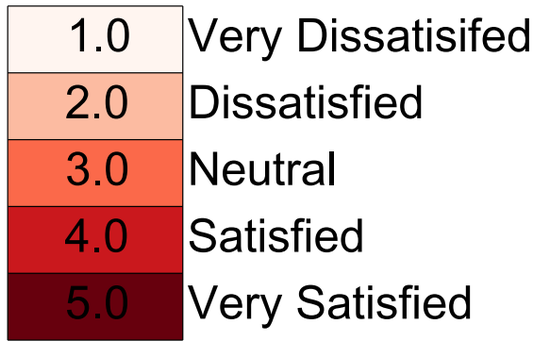

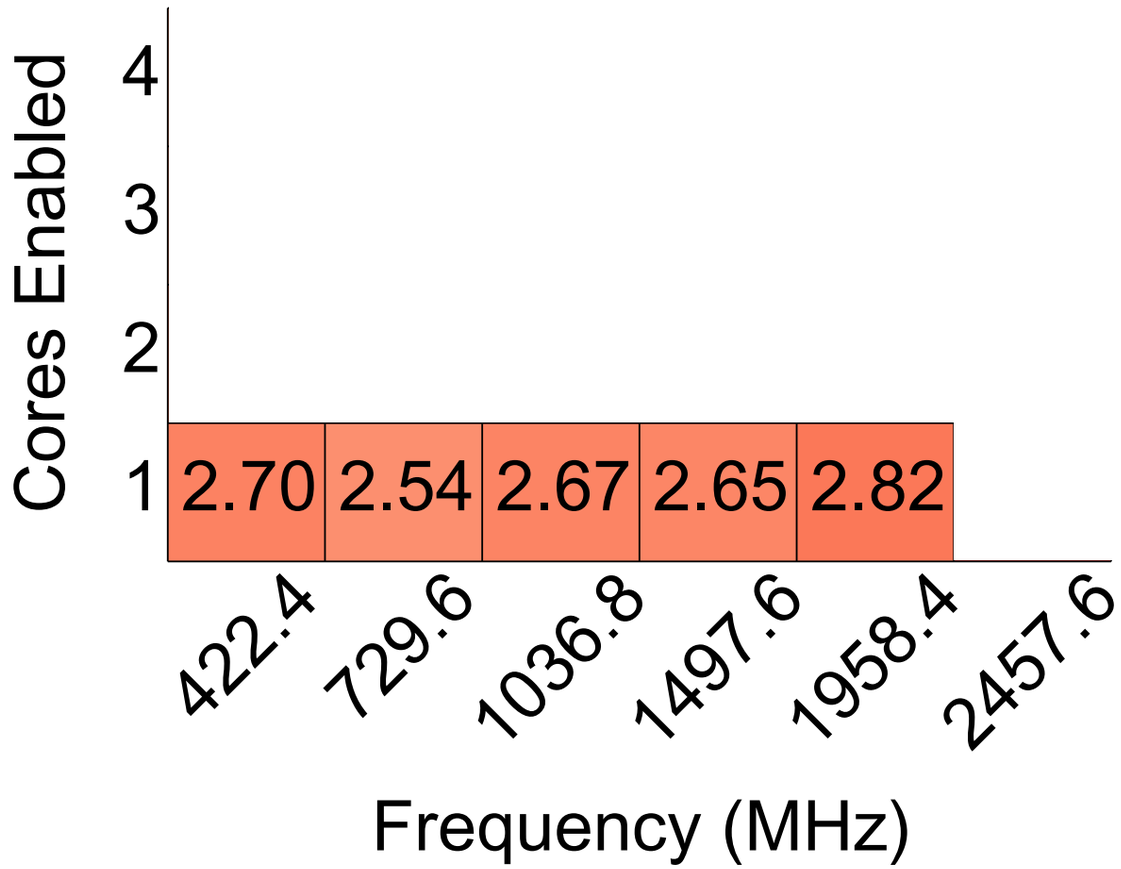

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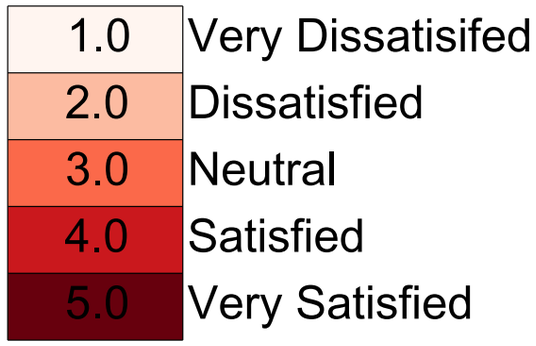
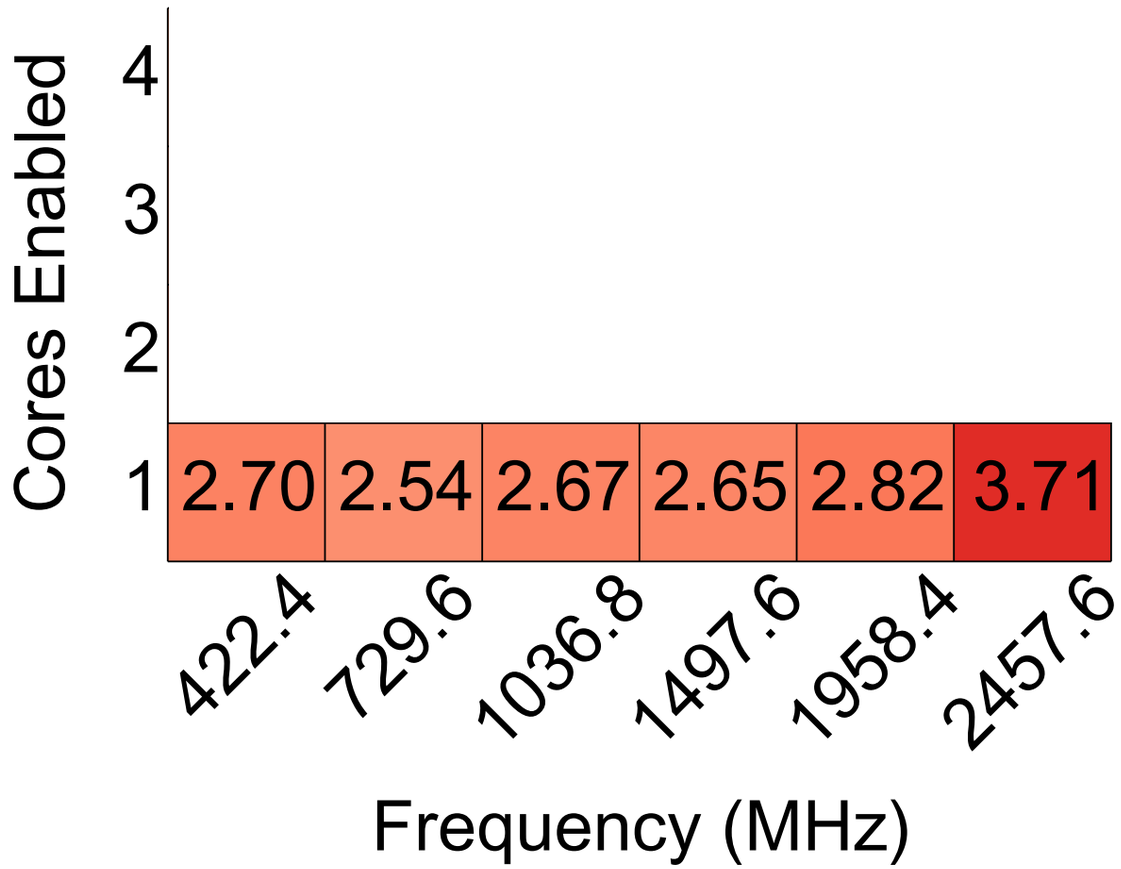
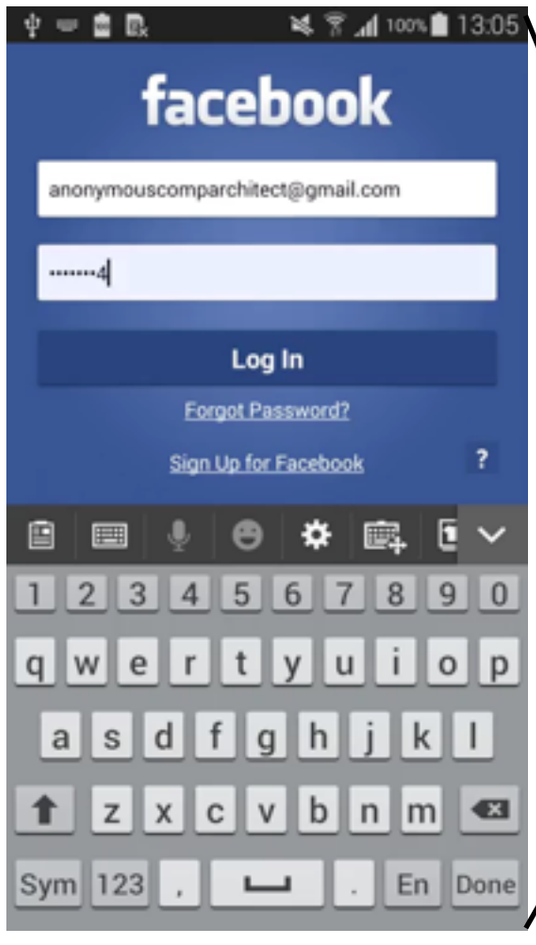
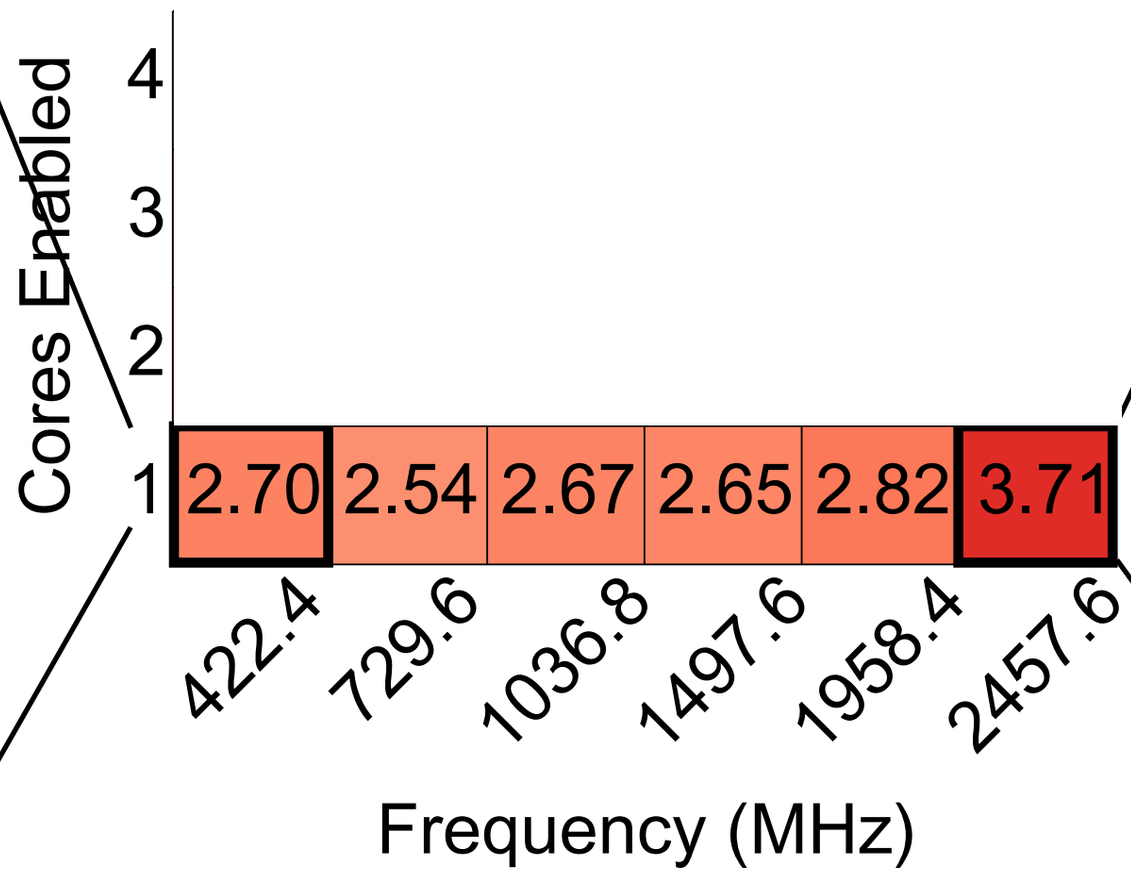


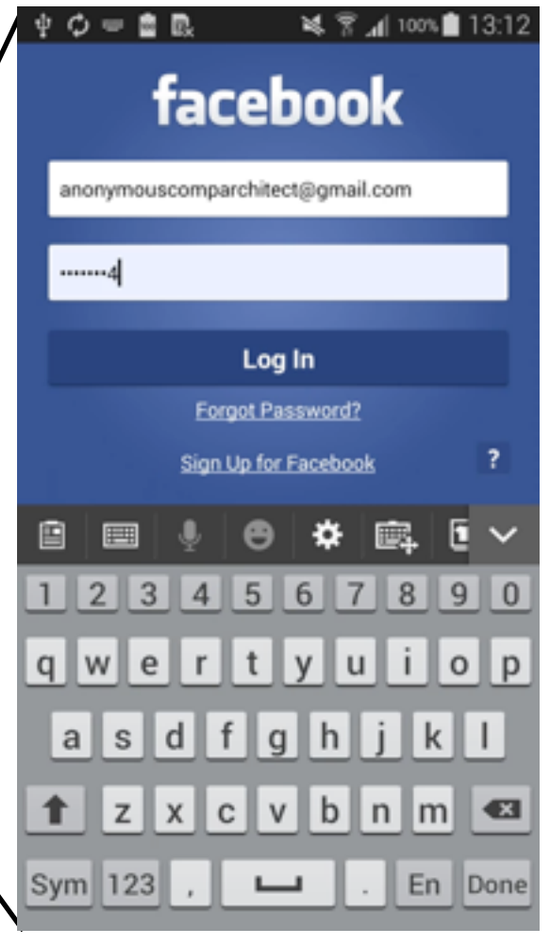


Do we need single-core performance?

1.0	Very Dissatisifed
2.0	Dissatisfied
3.0	Neutral
4.0	Satisfied
5.0	Very Satisfied







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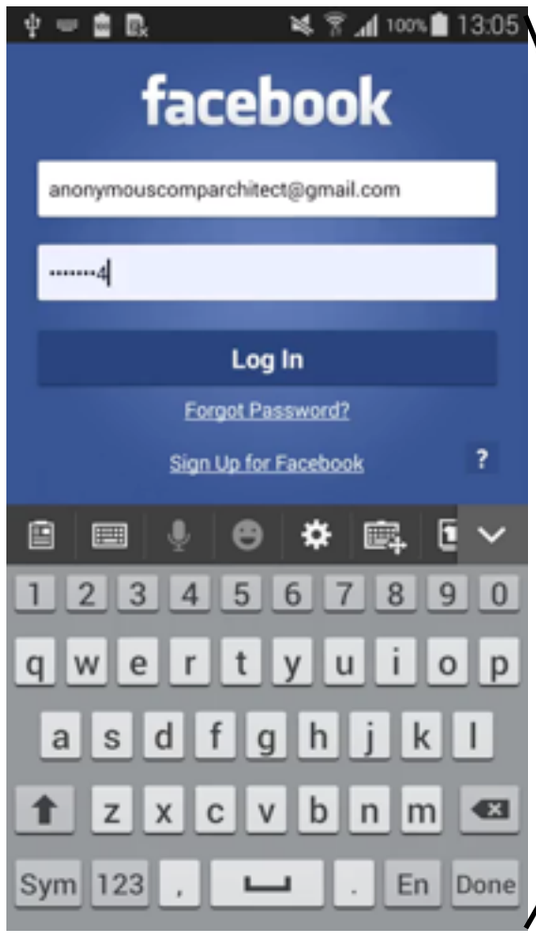
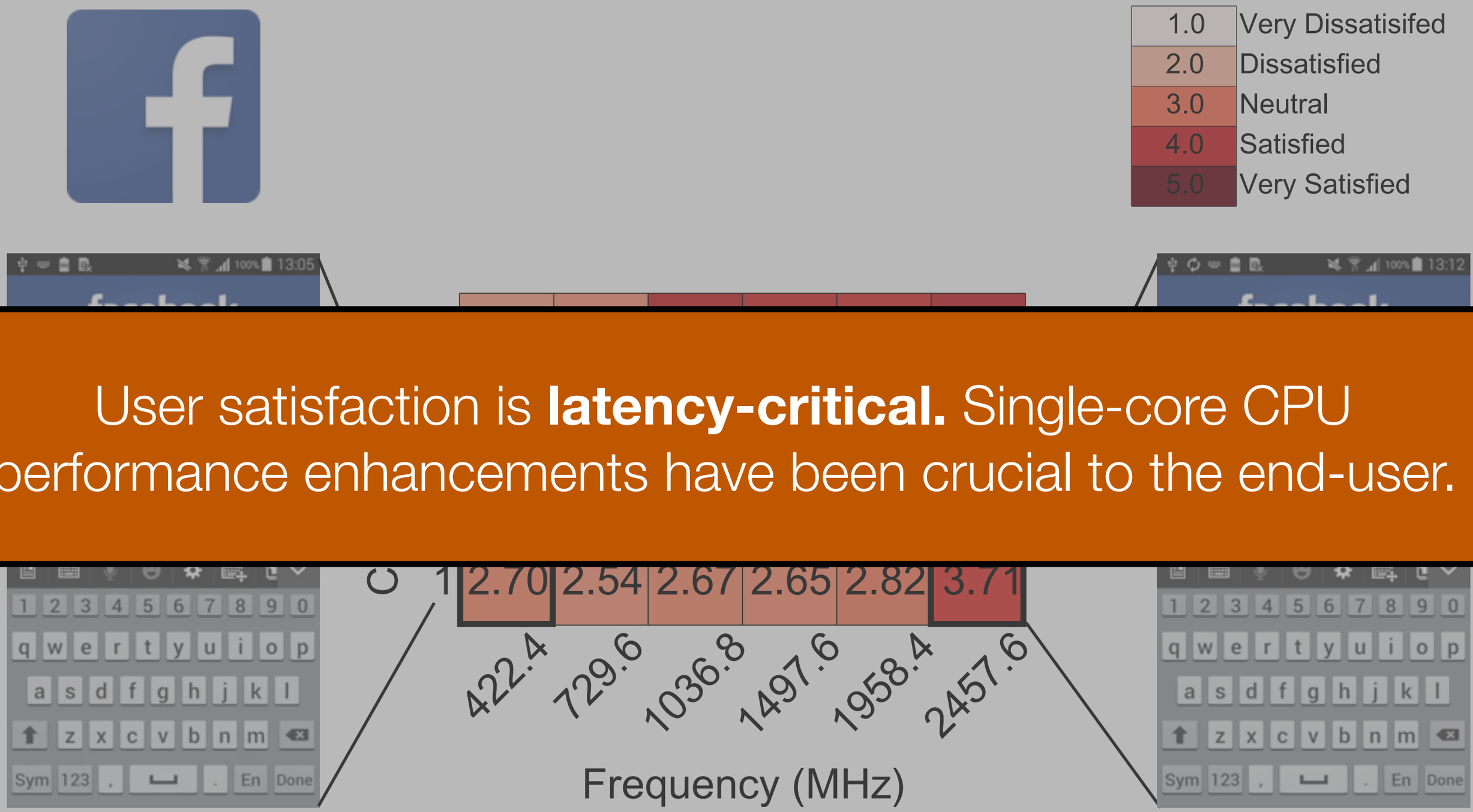


Cores Enabled	422.4	729.6	1036.8	1497.6	1958.4	2457.6
4	2.40	2.56	4.08	3.89	3.82	4.14
3	2.49	2.85	3.90	3.72	3.90	3.88
2	2.77	2.66	2.79	4.19	4.06	3.82
1	2.70	2.54	2.67	2.65	2.82	3.71

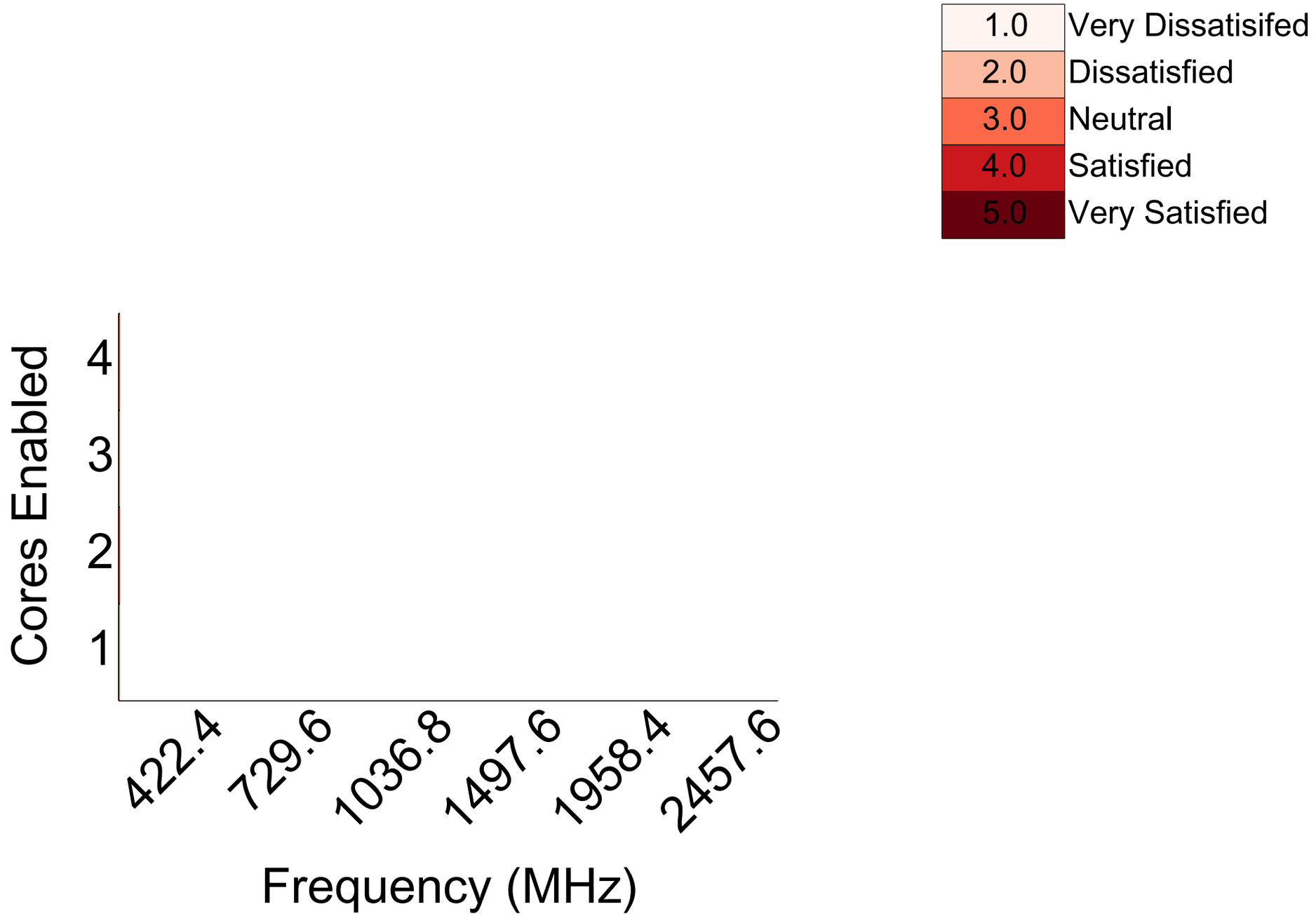
Frequency (MHz)

Do we need single-core performance?



User satisfaction is **latency-critical.** Single-core CPU performance enhancements have been crucial to the end-user.

Do we need multi-core performance?



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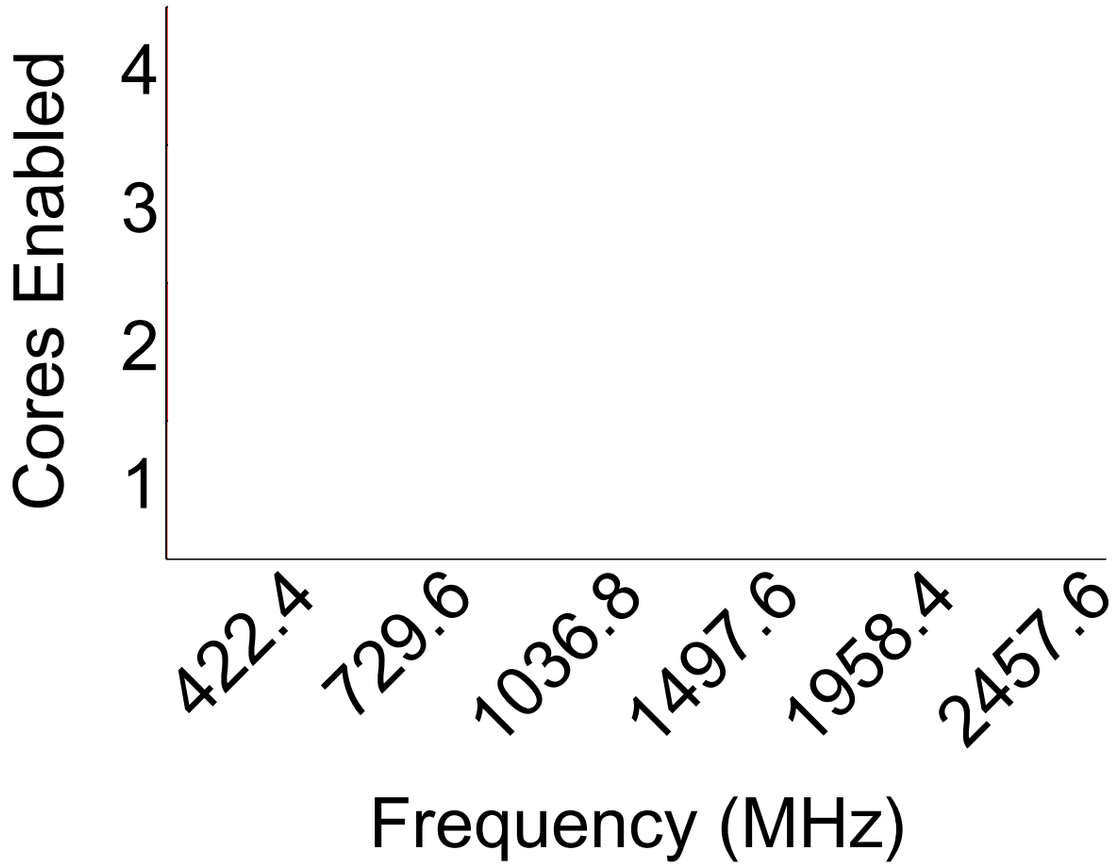

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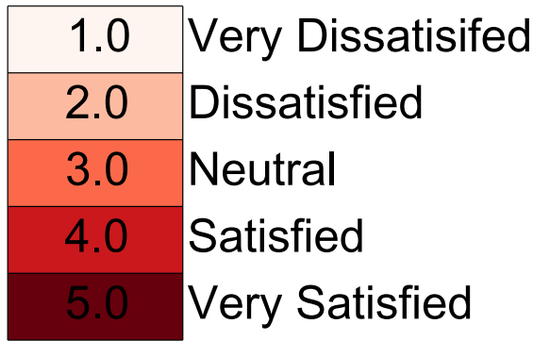

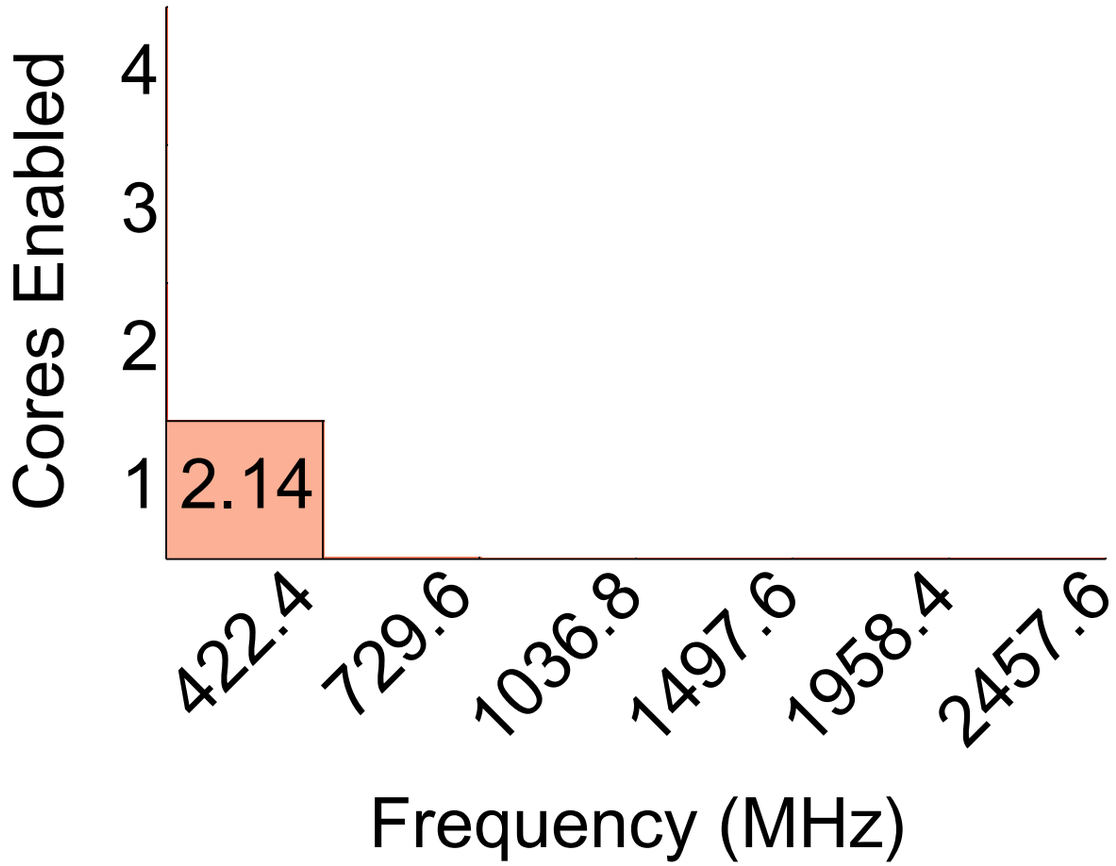

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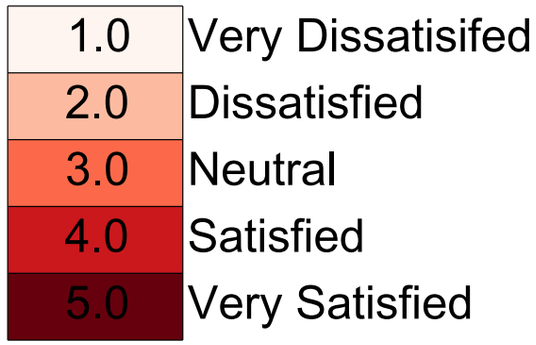

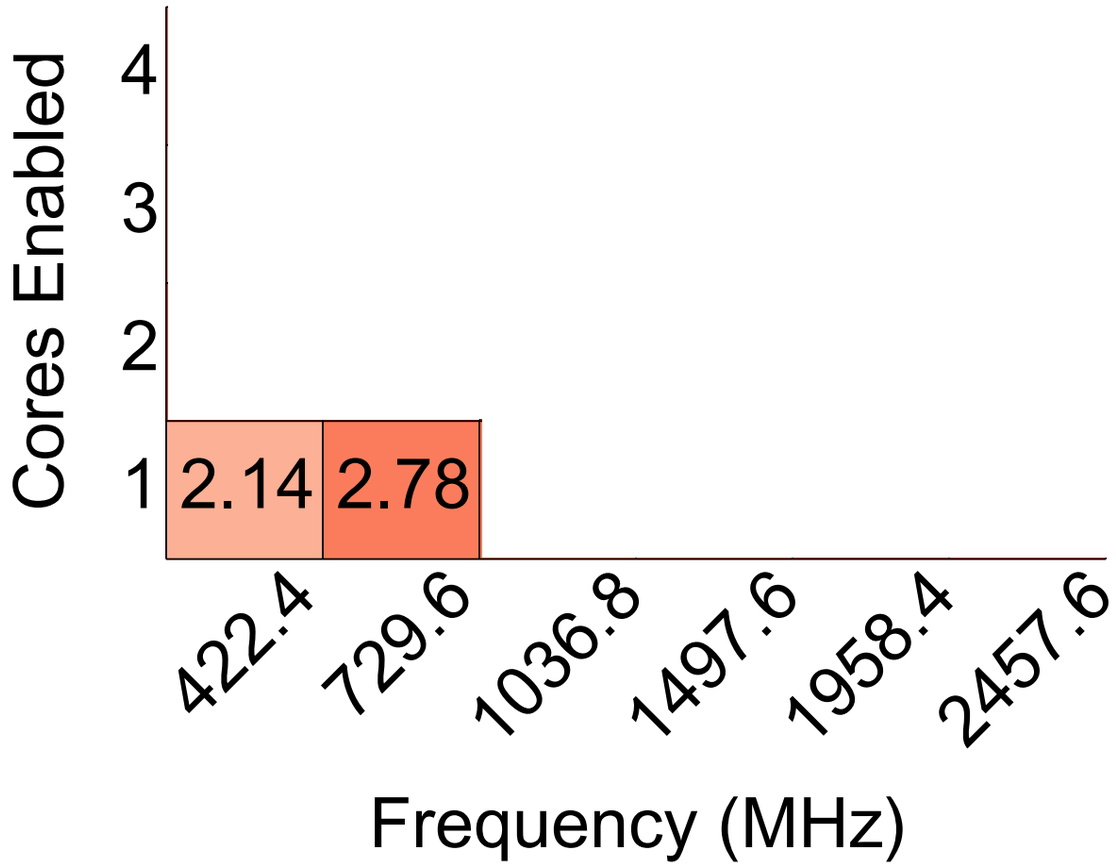

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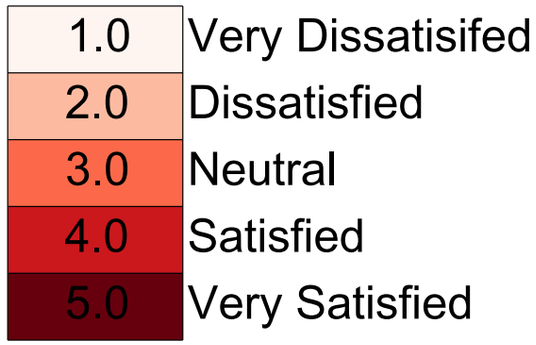

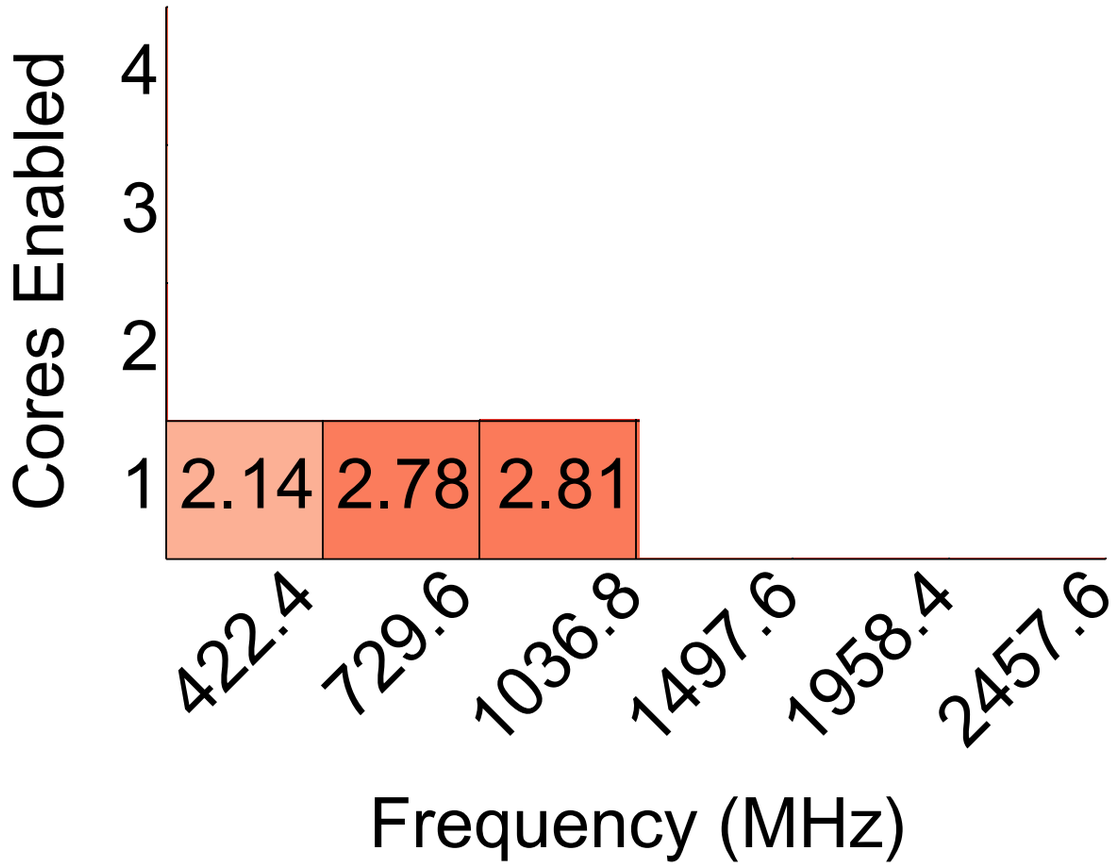

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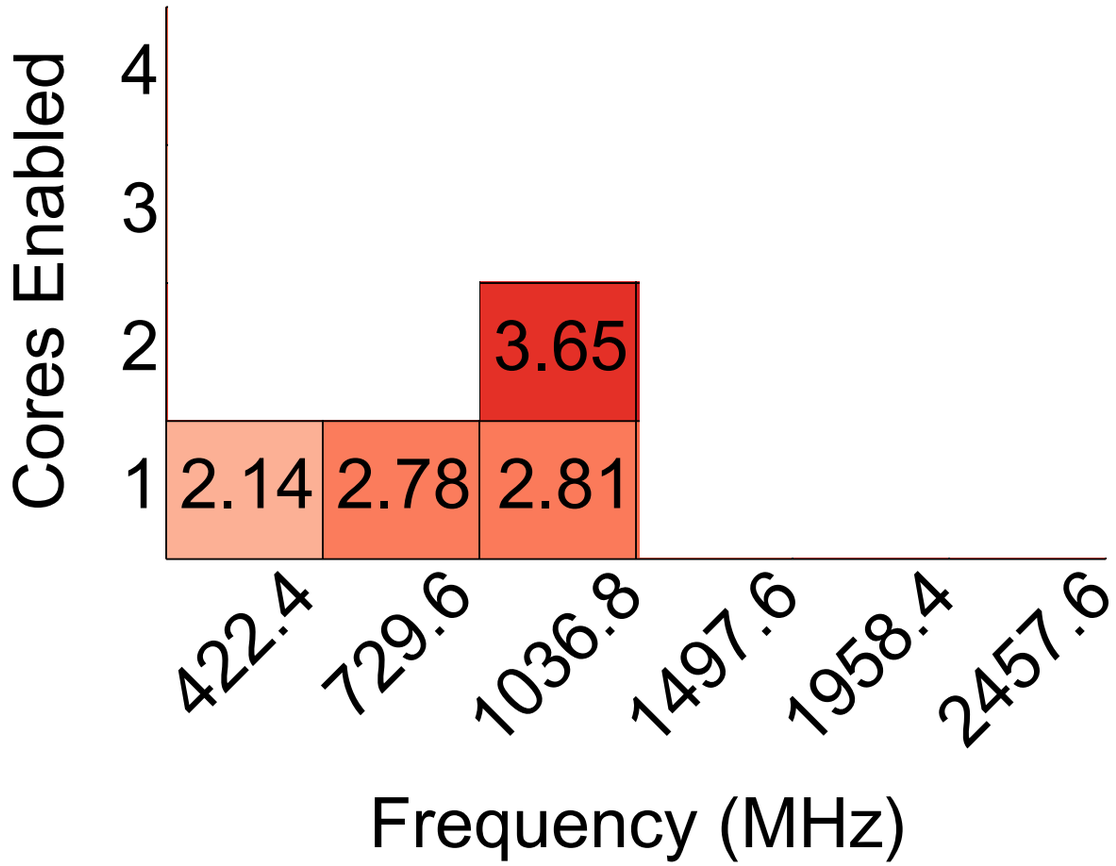
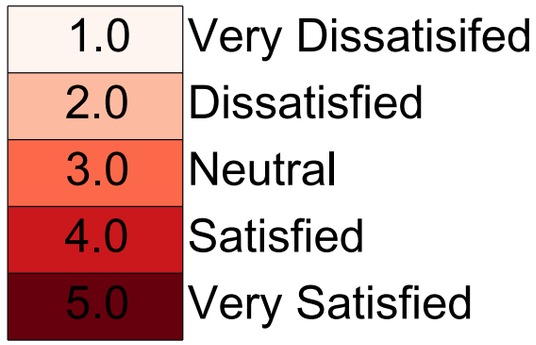
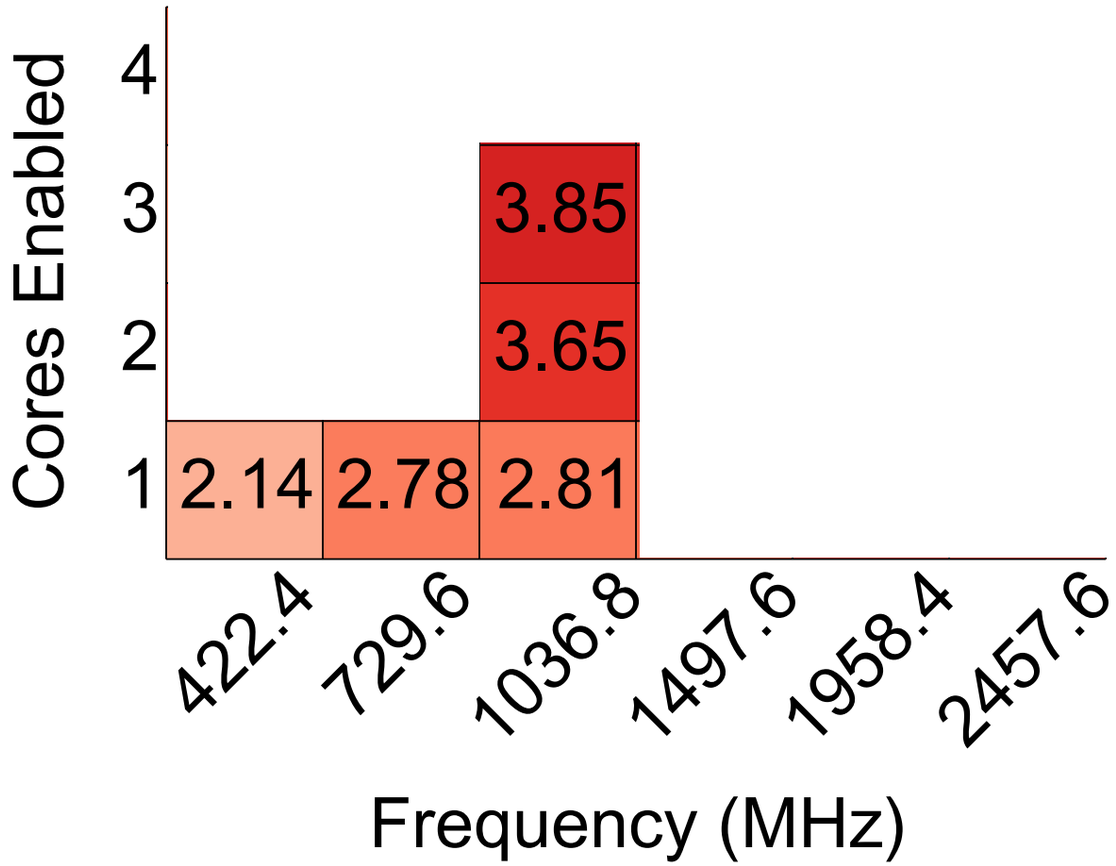


Do we need multi-core performance?





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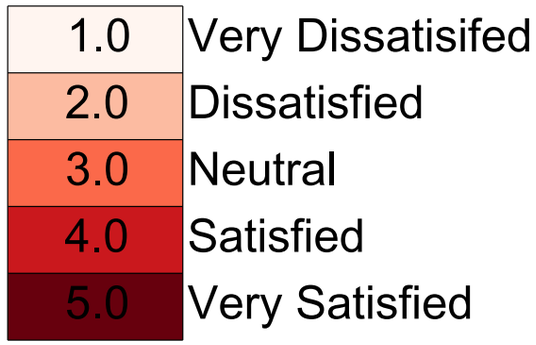

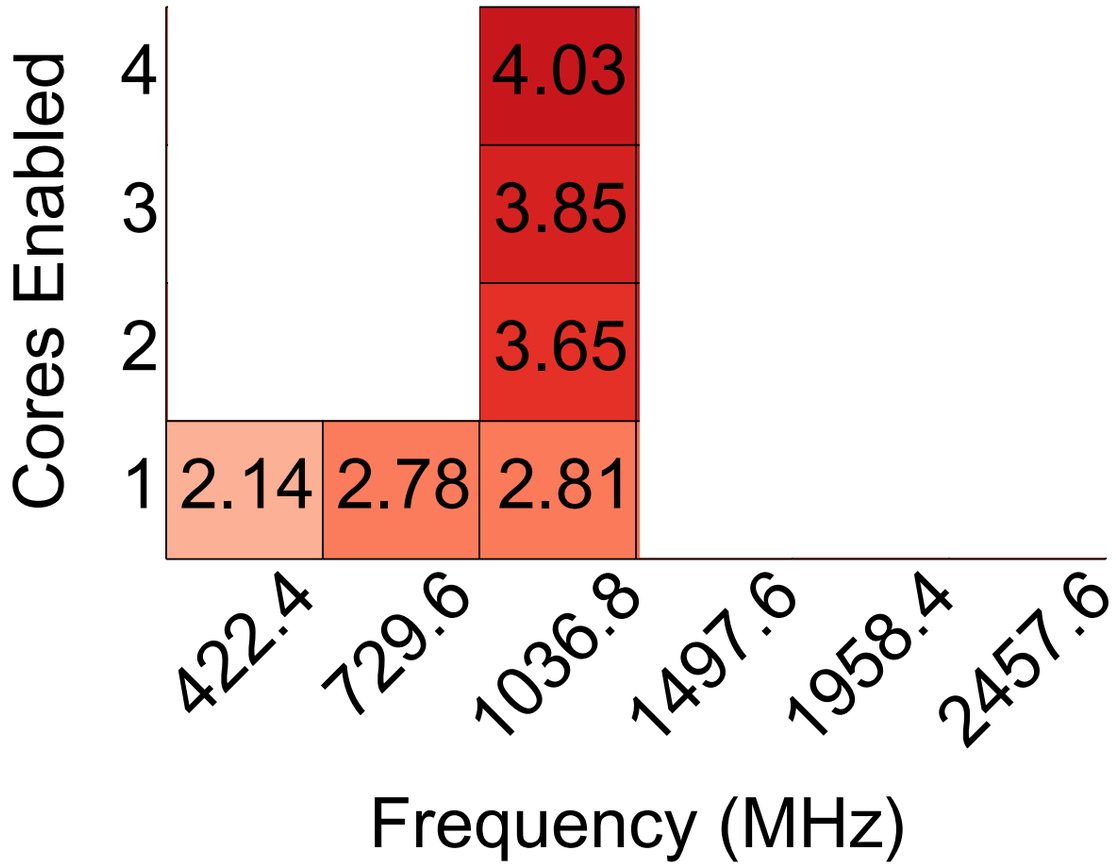

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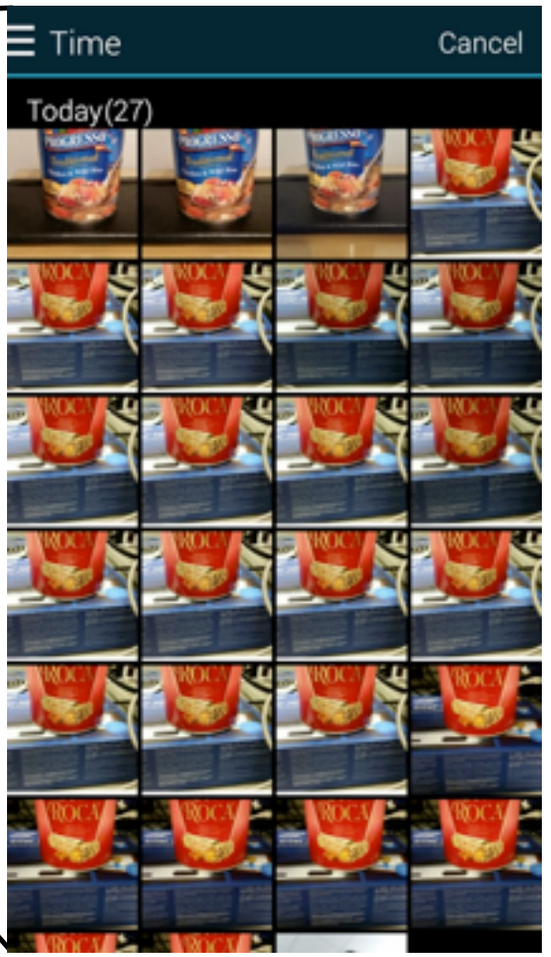
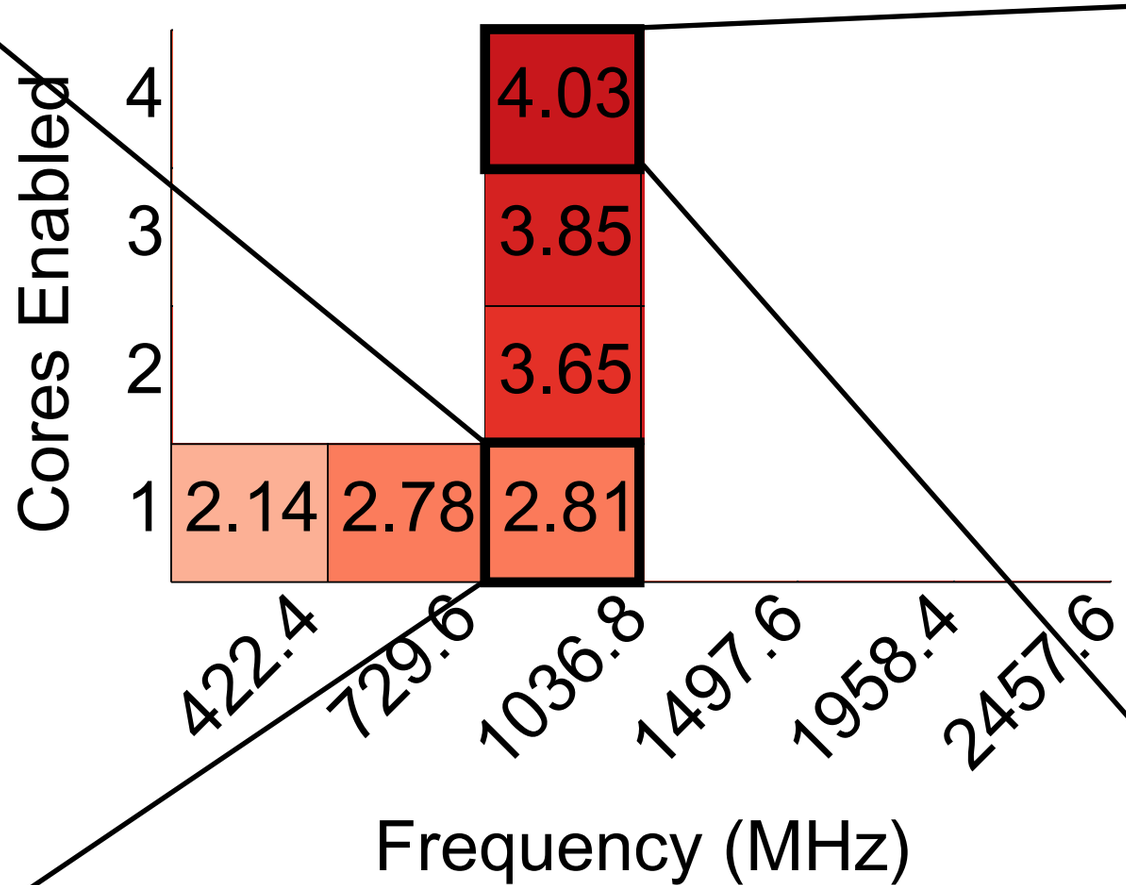
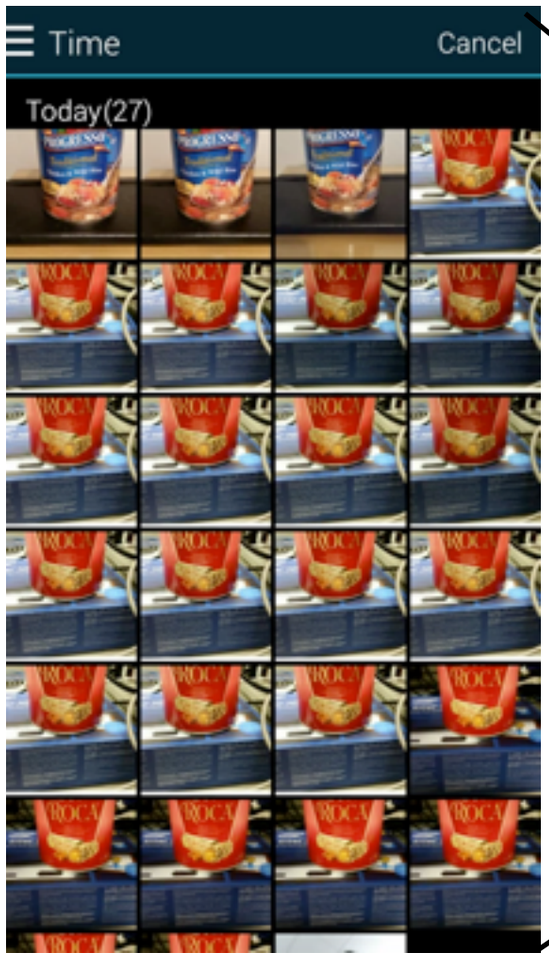
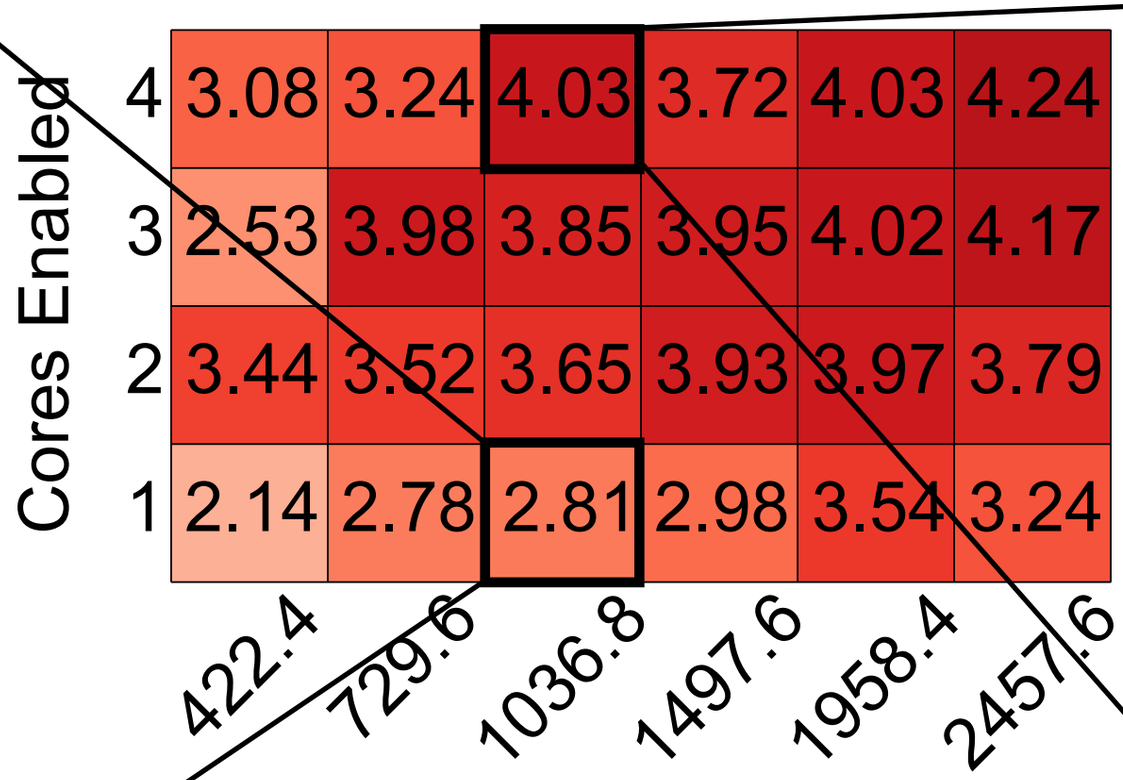


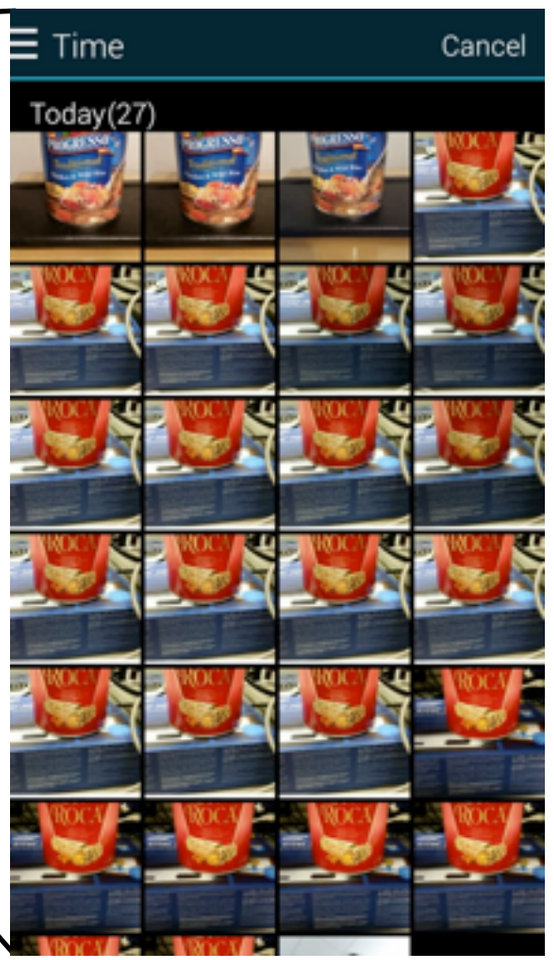


Do we need multi-core performance?

1.0	Very Dissatisifed
2.0	Dissatisfied
3.0	Neutral
4.0	Satisfied
5.0	Very Satisfied







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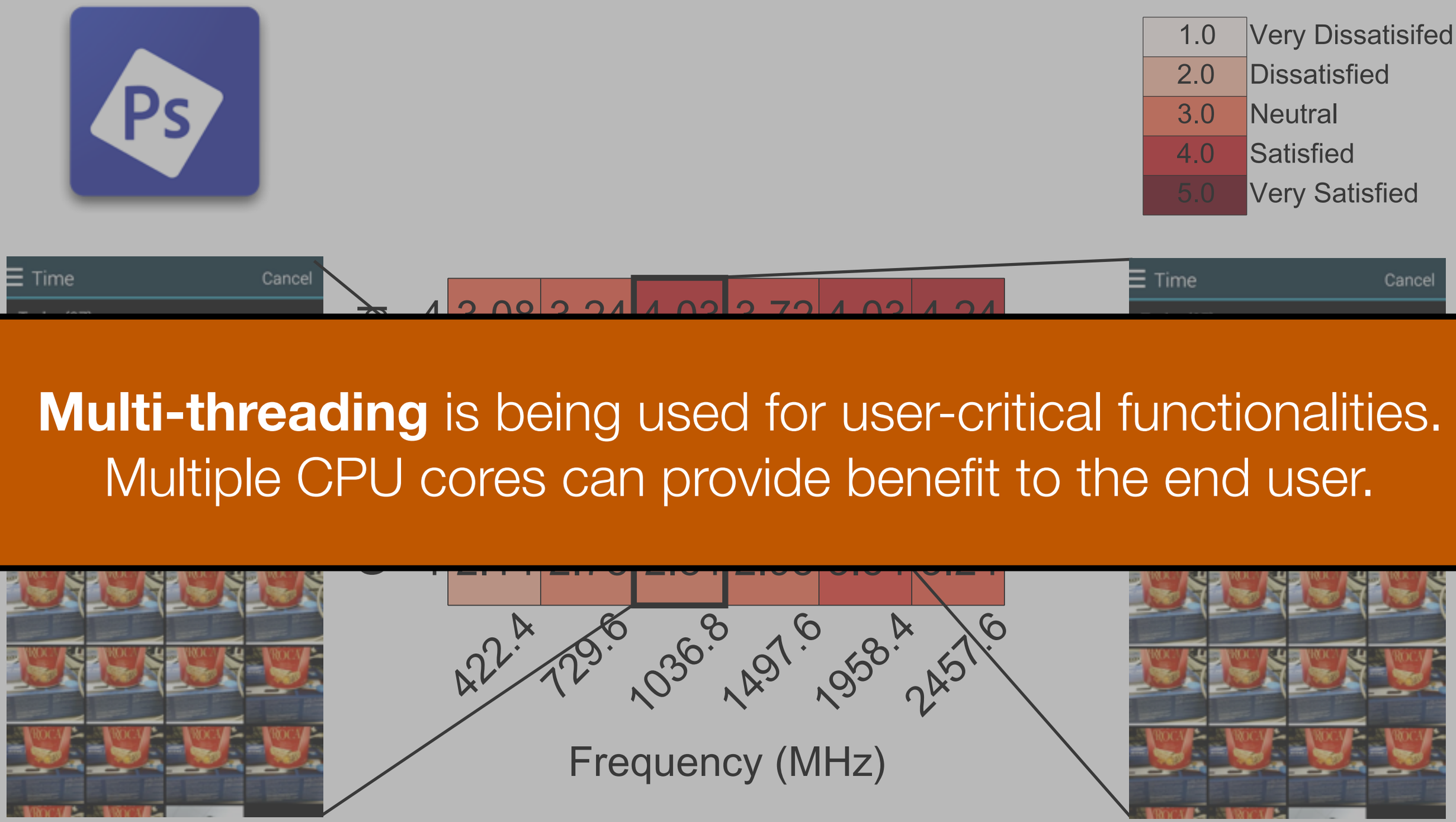
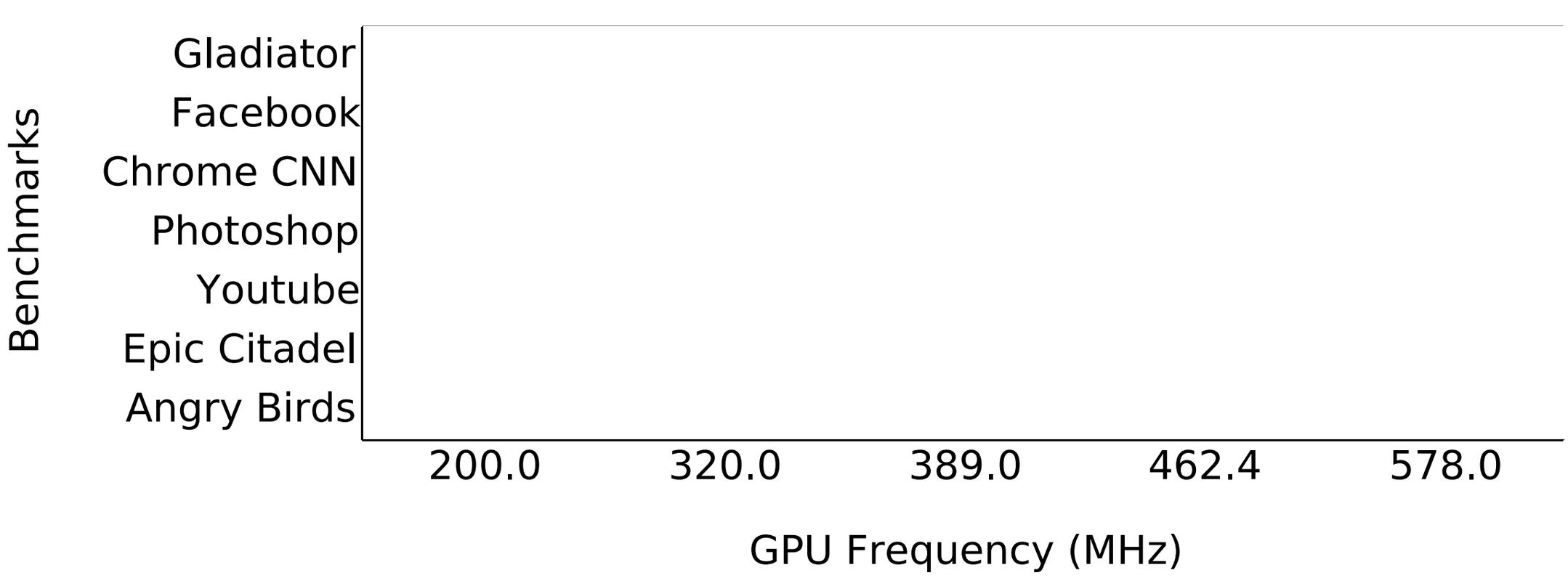


Multi-threading is being used for user-critical functionalities.
Multiple CPU cores can provide benefit to the end user.

Does graphics performance matter more than CPU performance?



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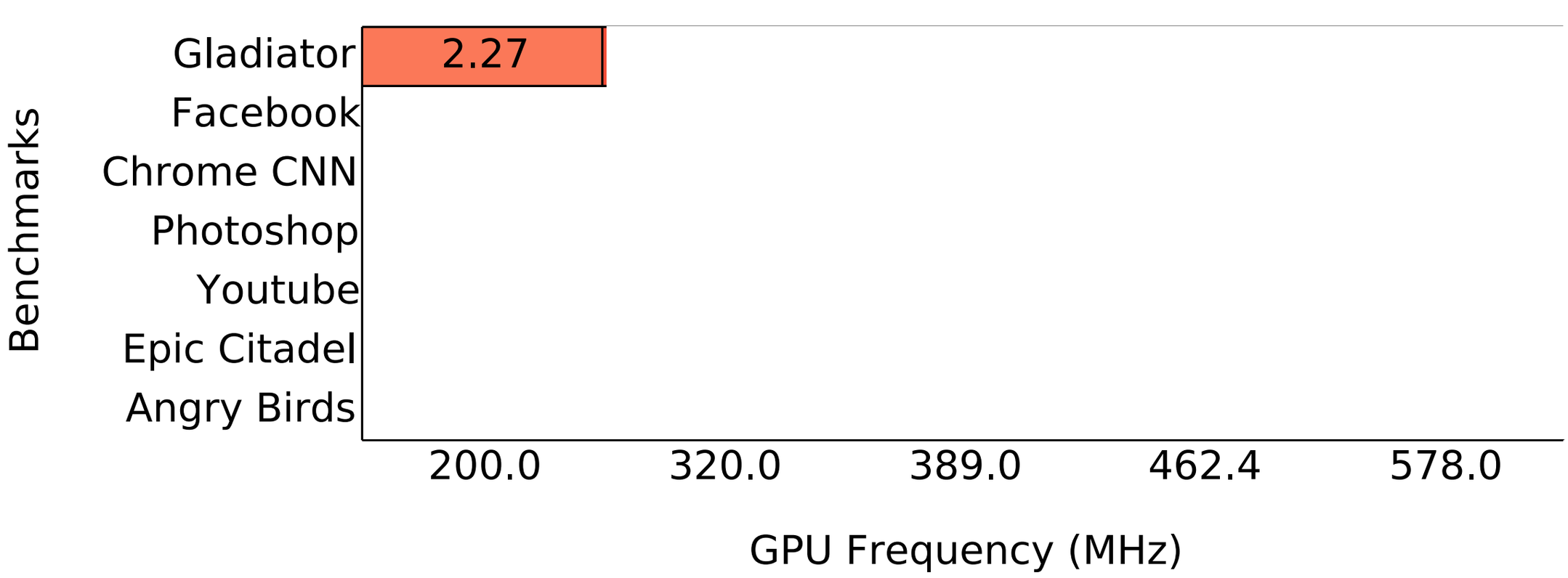

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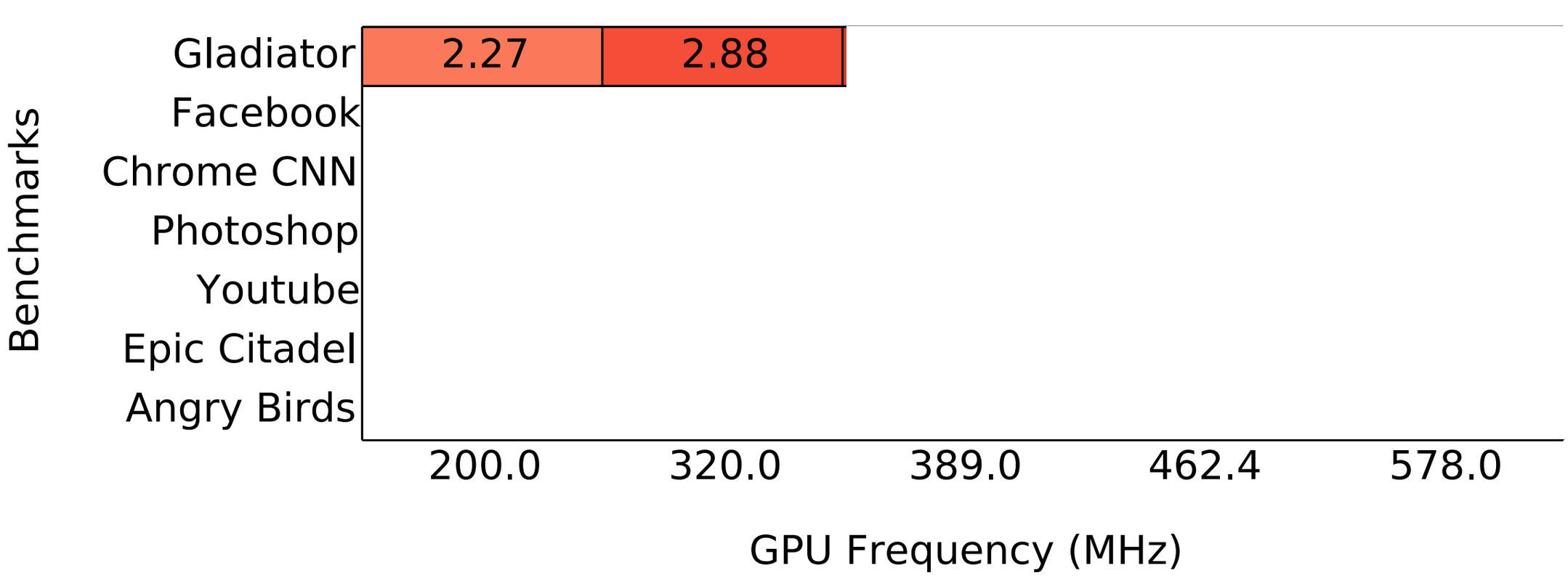

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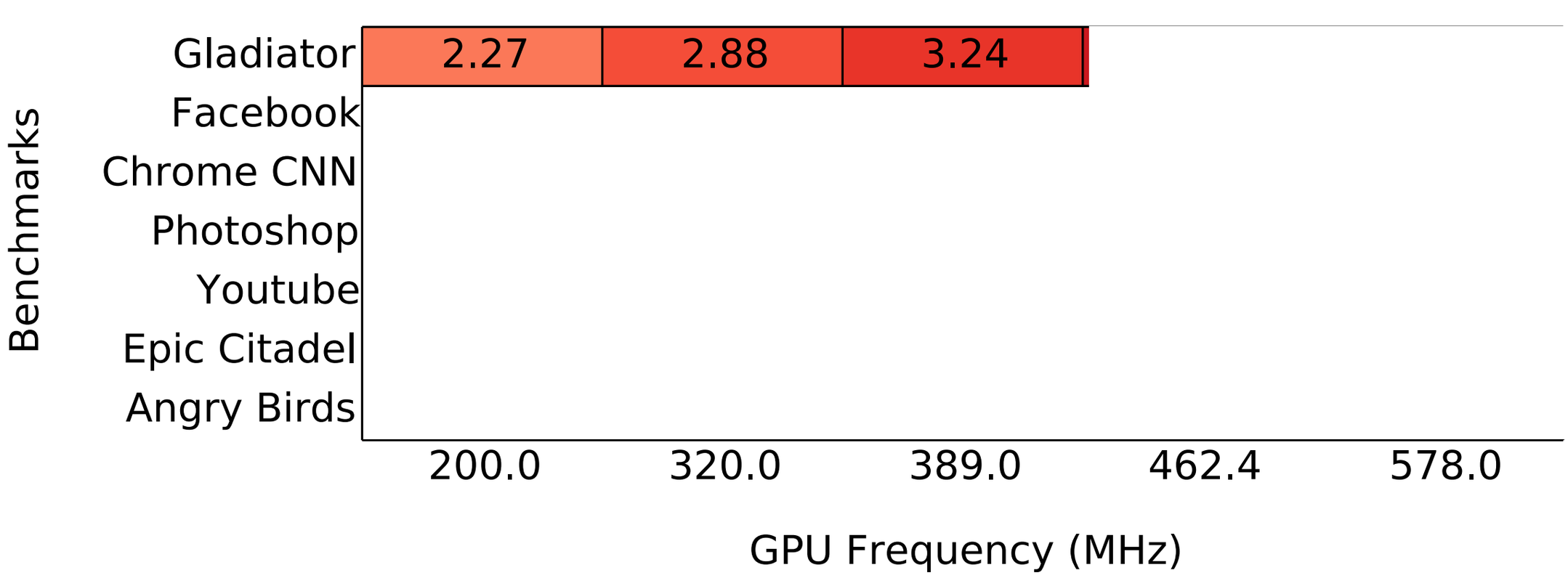

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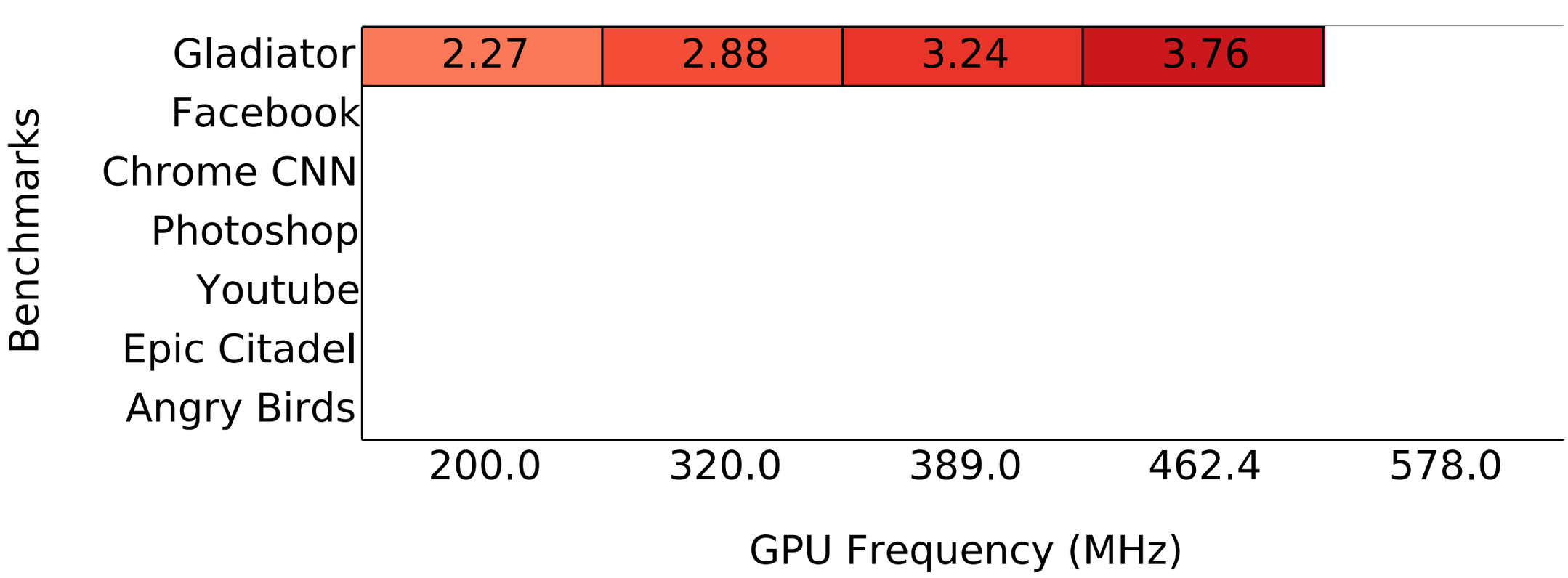

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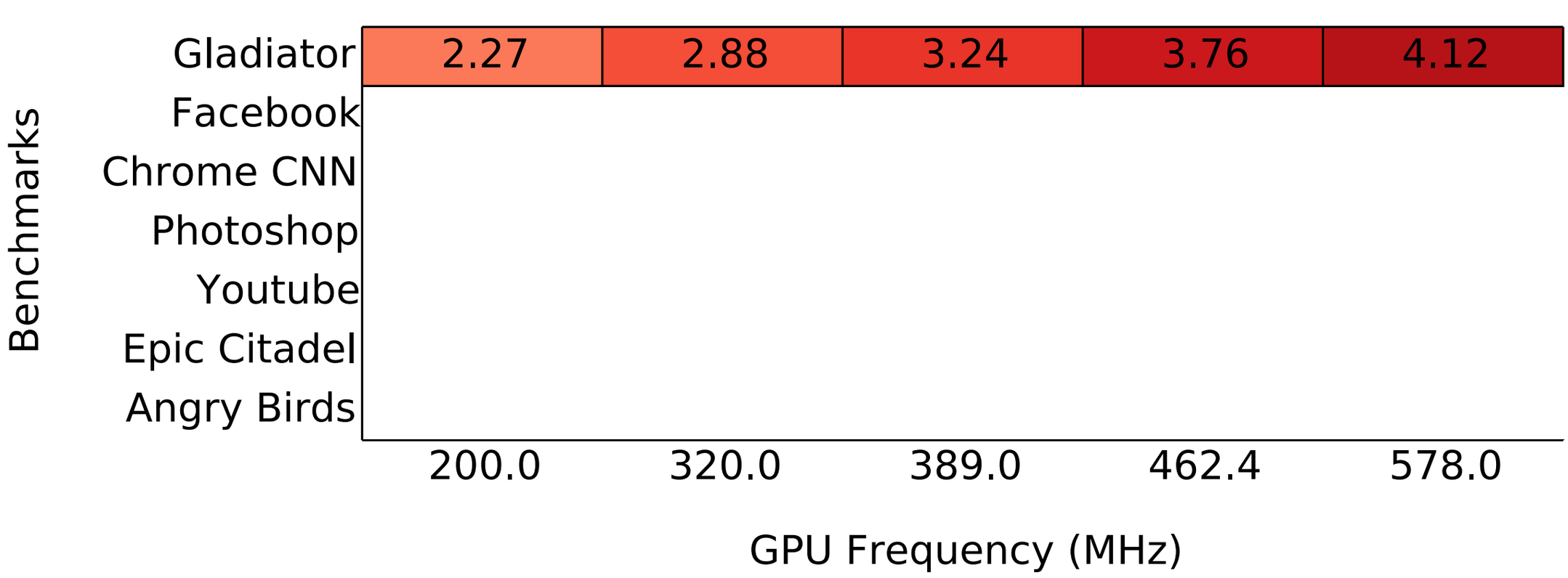

Does graphics performance matter more than CPU performance?

Benchmarks	200.0	320.0	389.0	462.4	578.0
Gladiator	2.27	2.88	3.24	3.76	4.12
Facebook	4.06	3.89	4.04	3.94	4.14
Chrome CNN	4.23	4.31	4.22	4.18	4.19
Photoshop	4.19	4.00	4.19	4.17	4.24
Youtube	4.38	4.38	4.31	4.37	4.18
Epic Citadel	4.44	4.51	4.48	4.57	4.33
Angry Birds	4.23	4.57	4.44	4.30	4.60

GPU Frequency (MHz)

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GPU Frequency (MHz)

Does graphics performance matter more than CPU performance?

Even amongst applications that make use of the GPU and other accelerators, end-users are **sensitive to CPU performance.**

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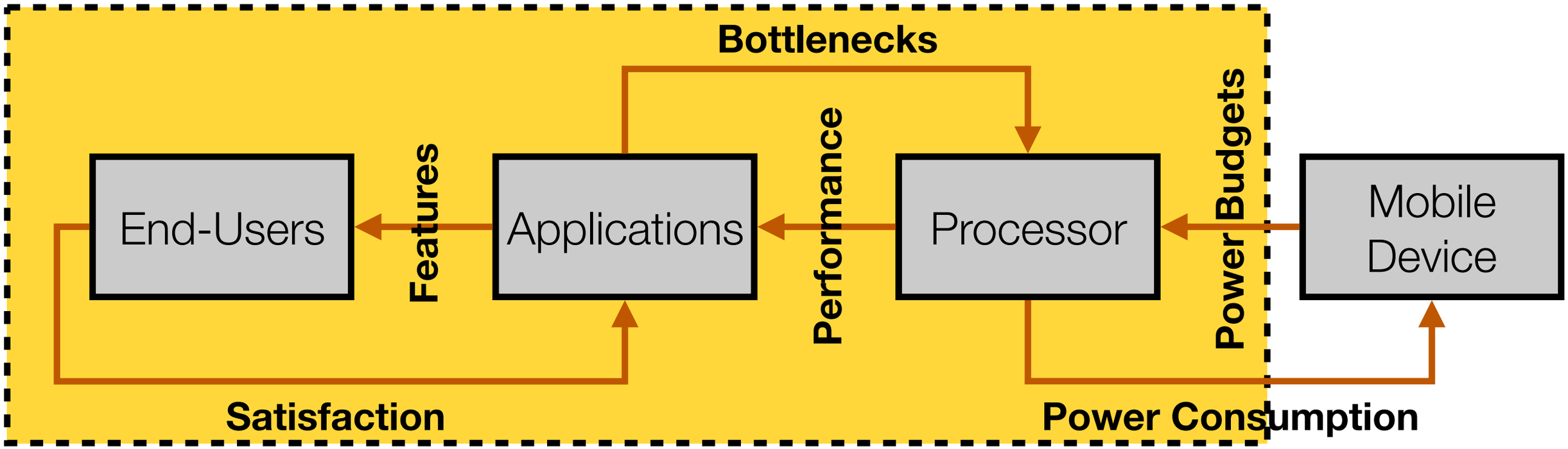
At the Mercy of Power Constraints



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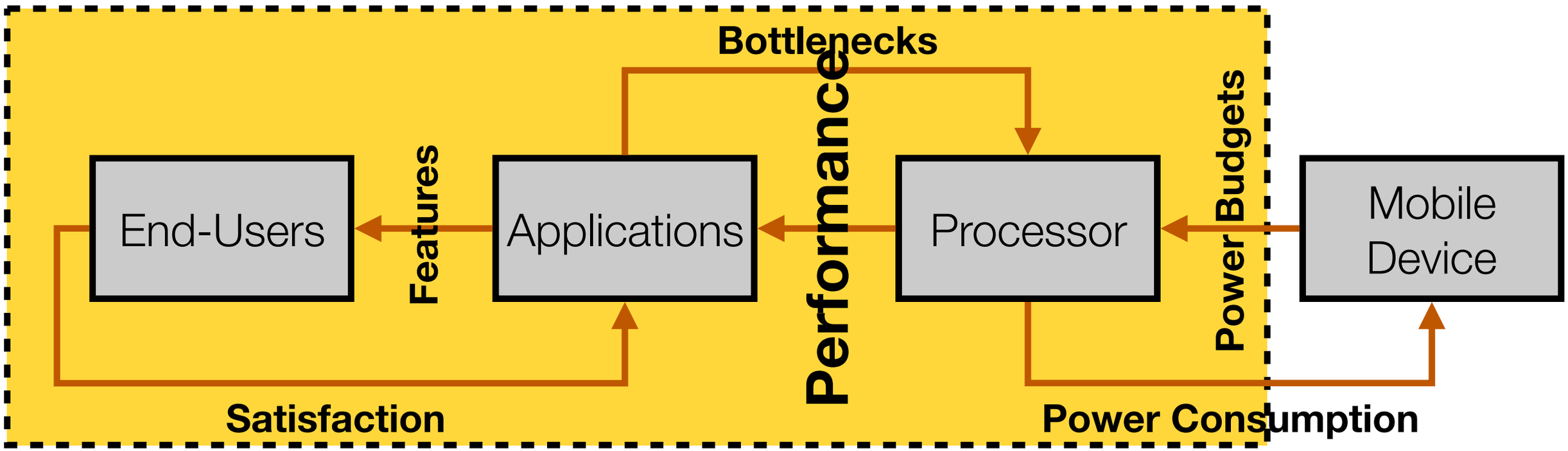

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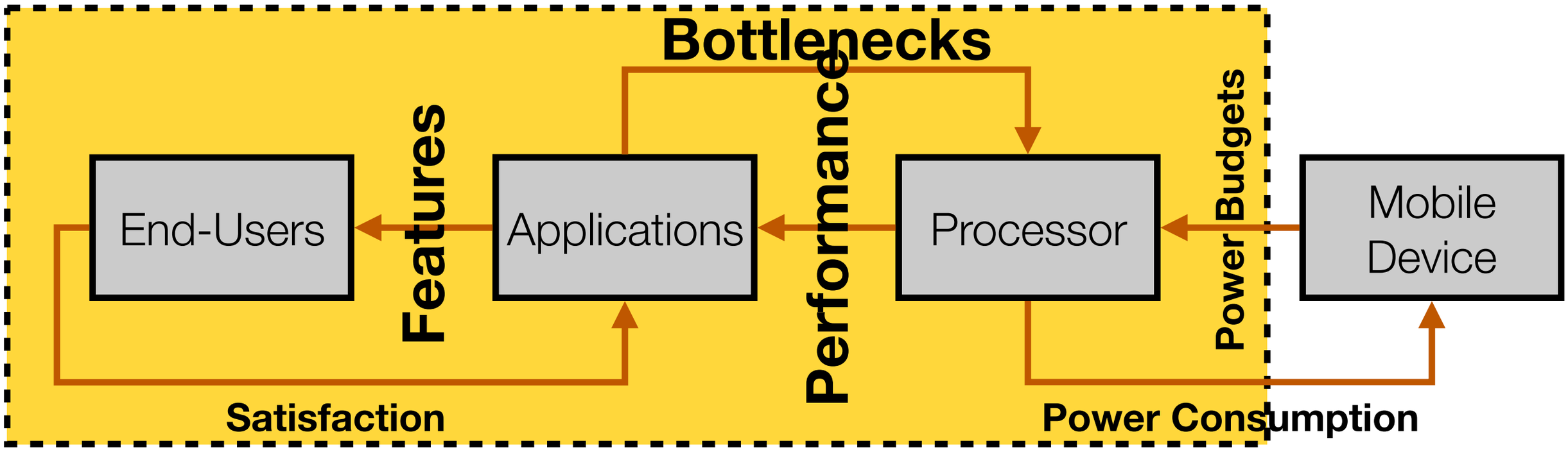

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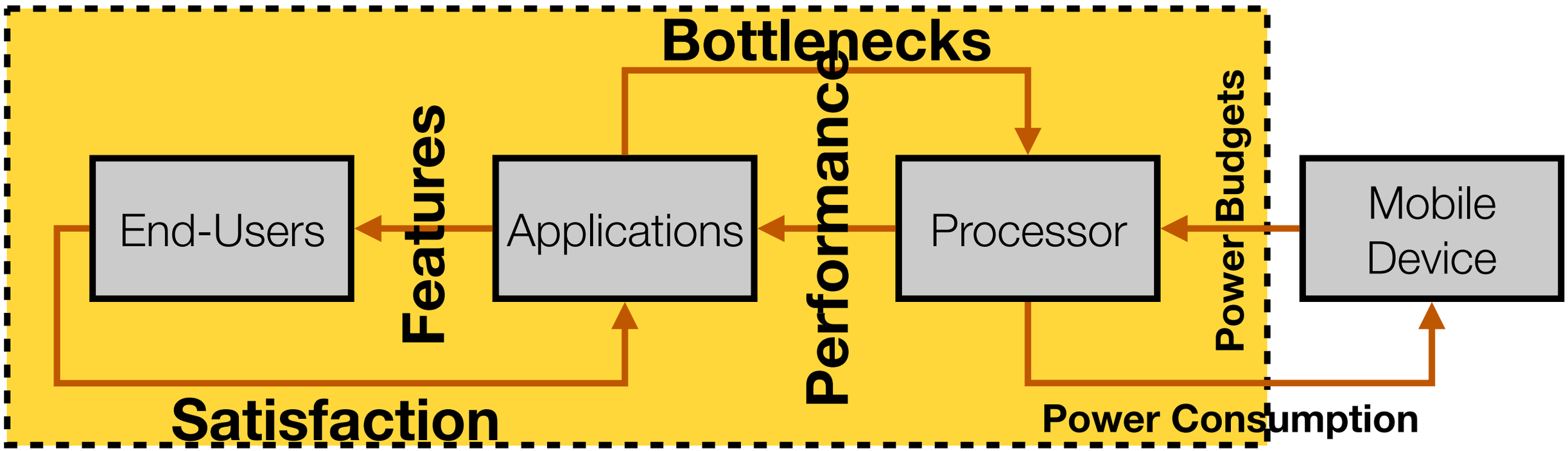

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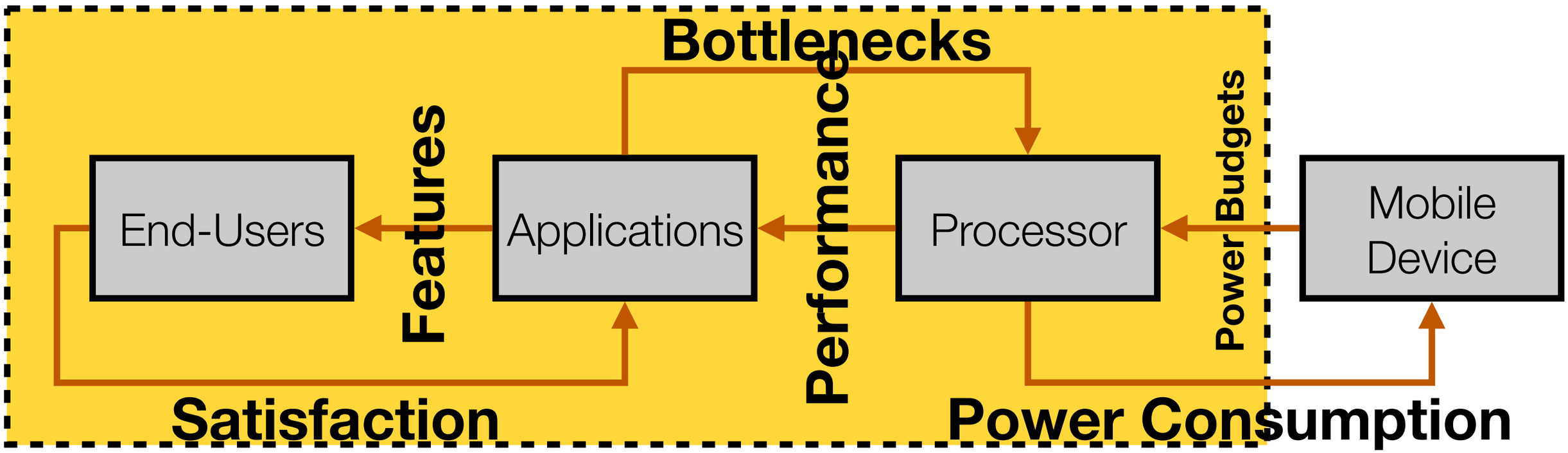

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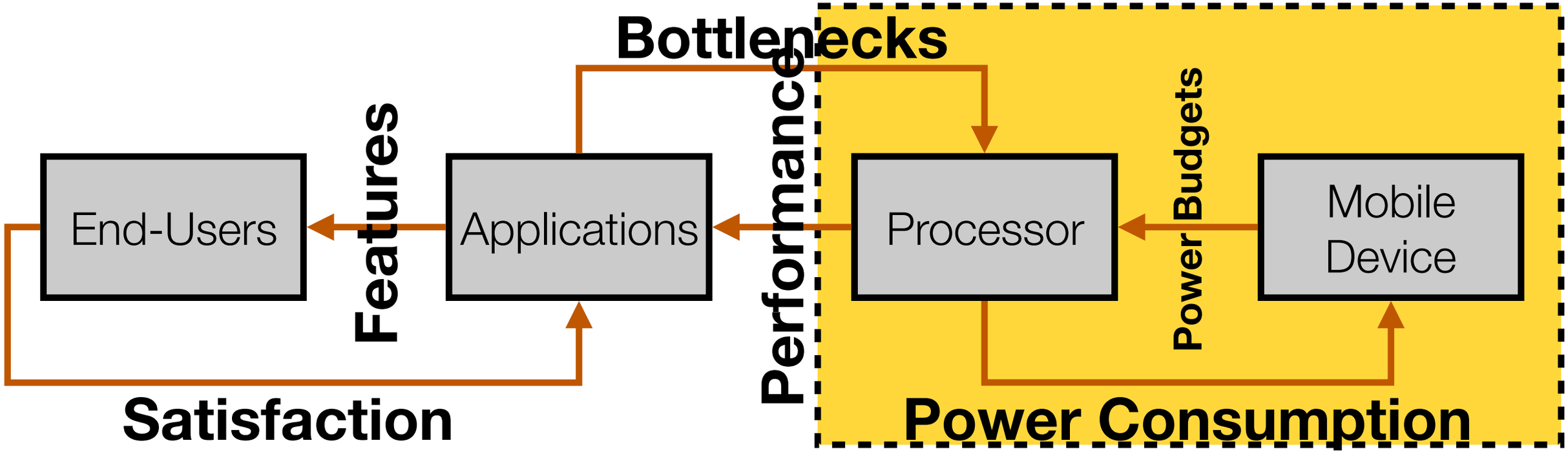

How has the rest of the mobile device evolved around the CPU?

Sharing the Power Budget: Device-level

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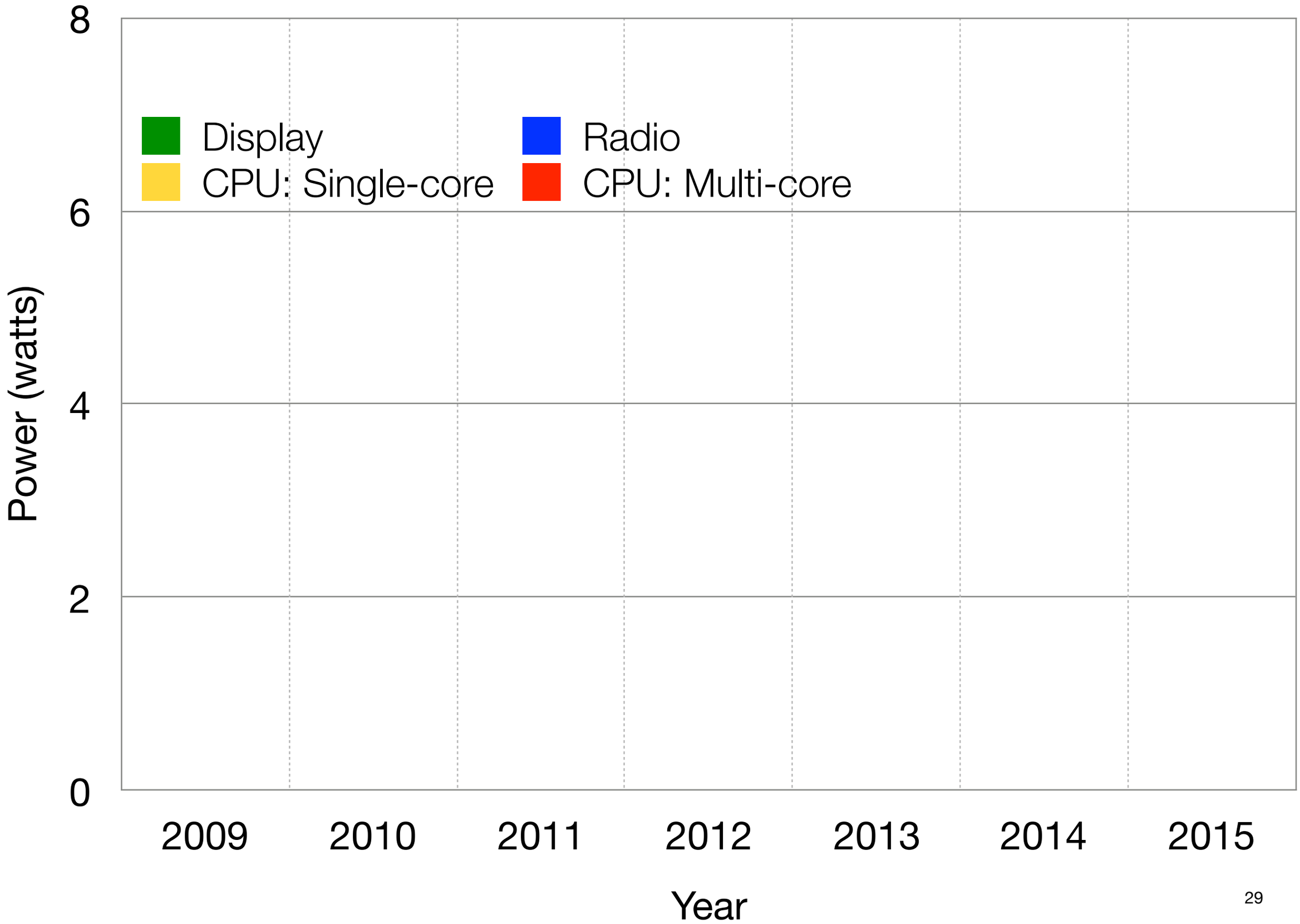

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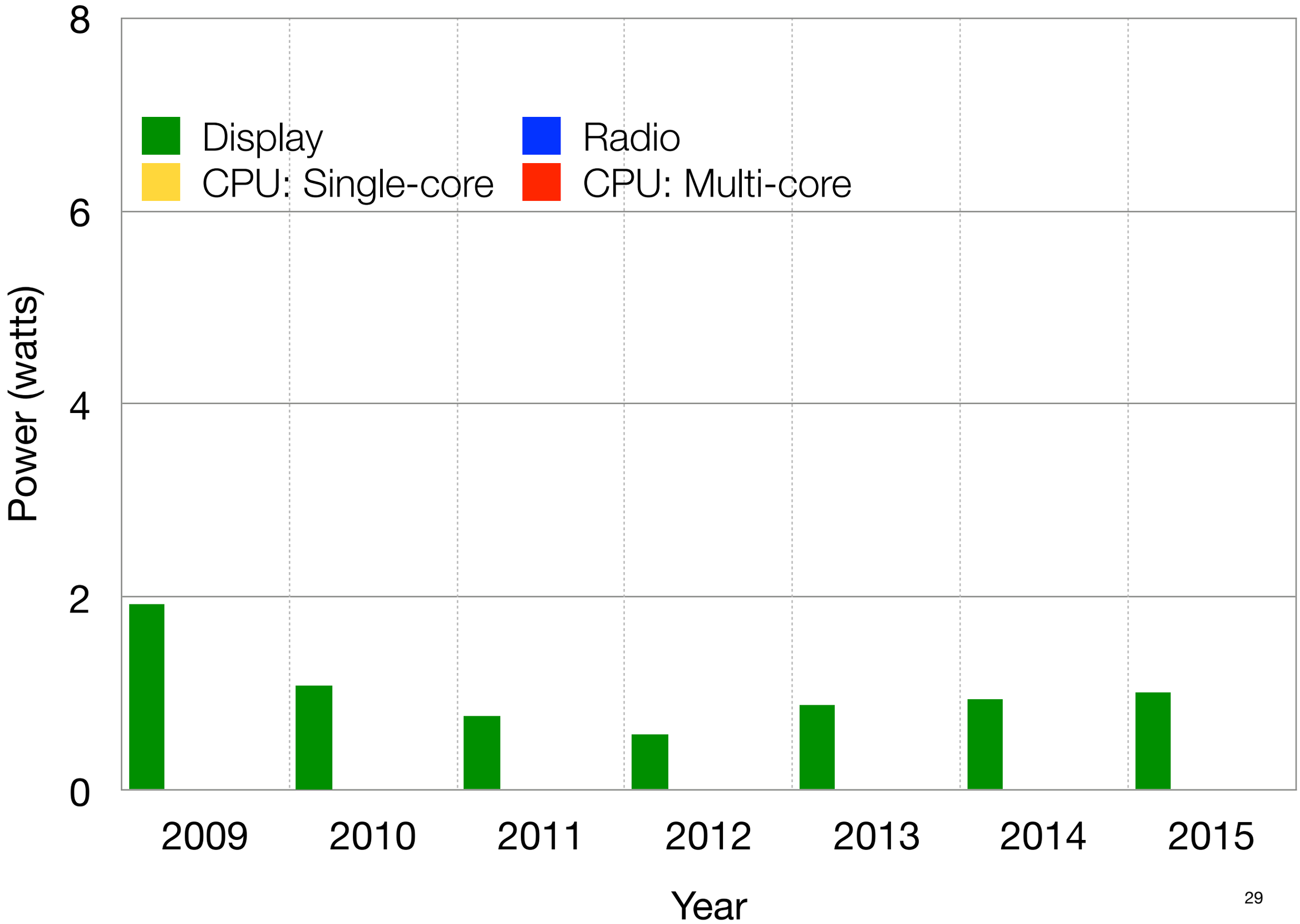

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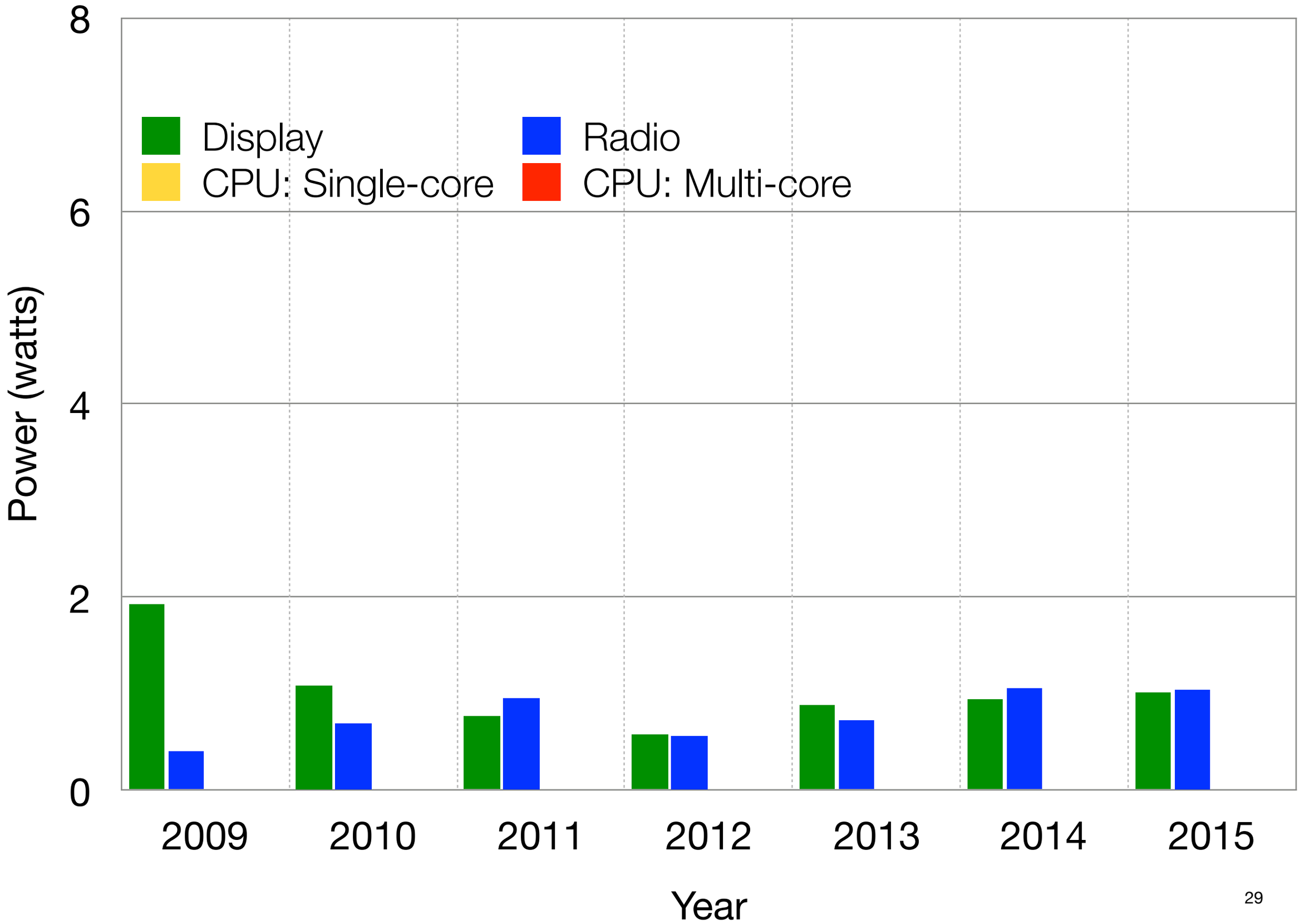

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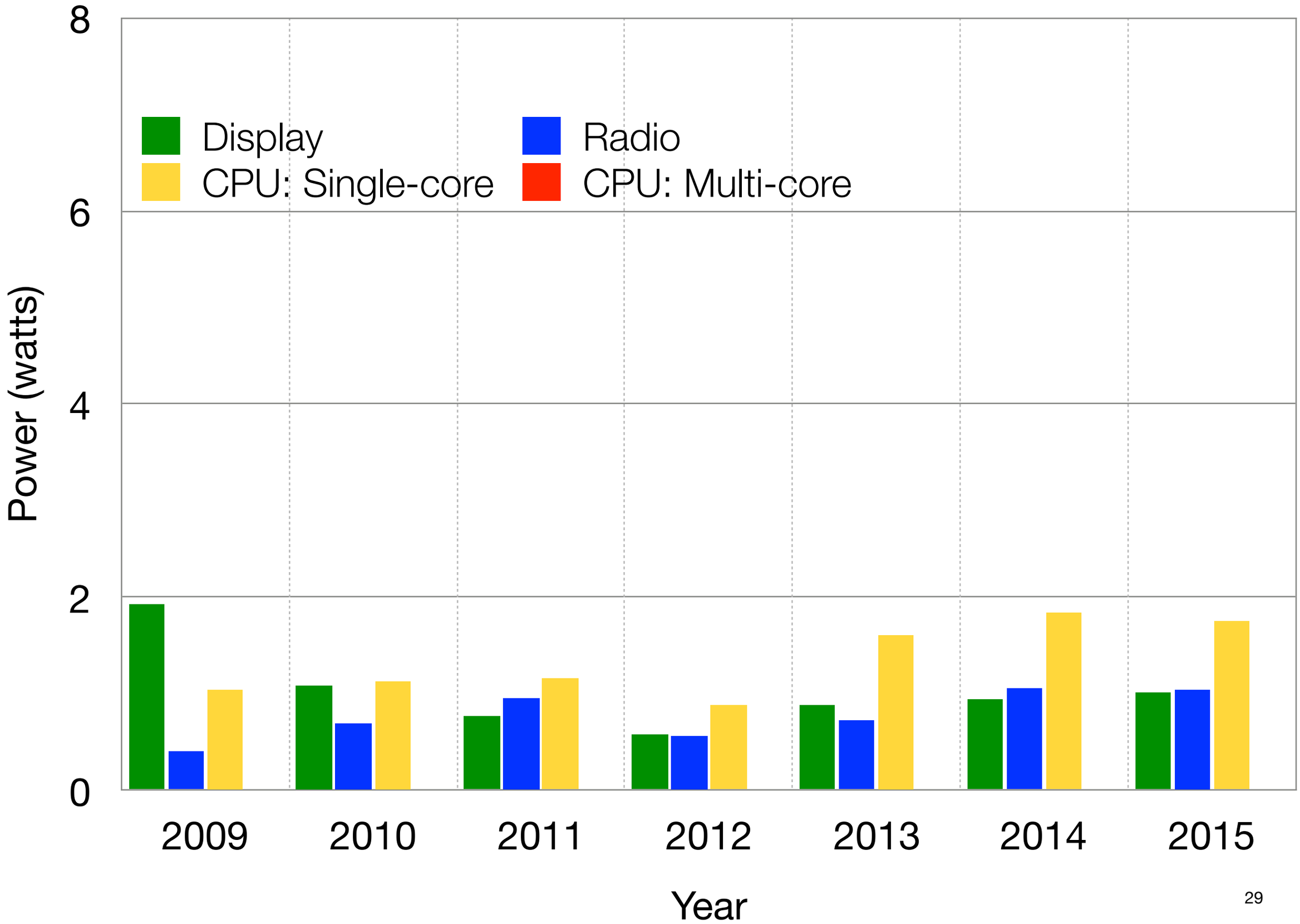

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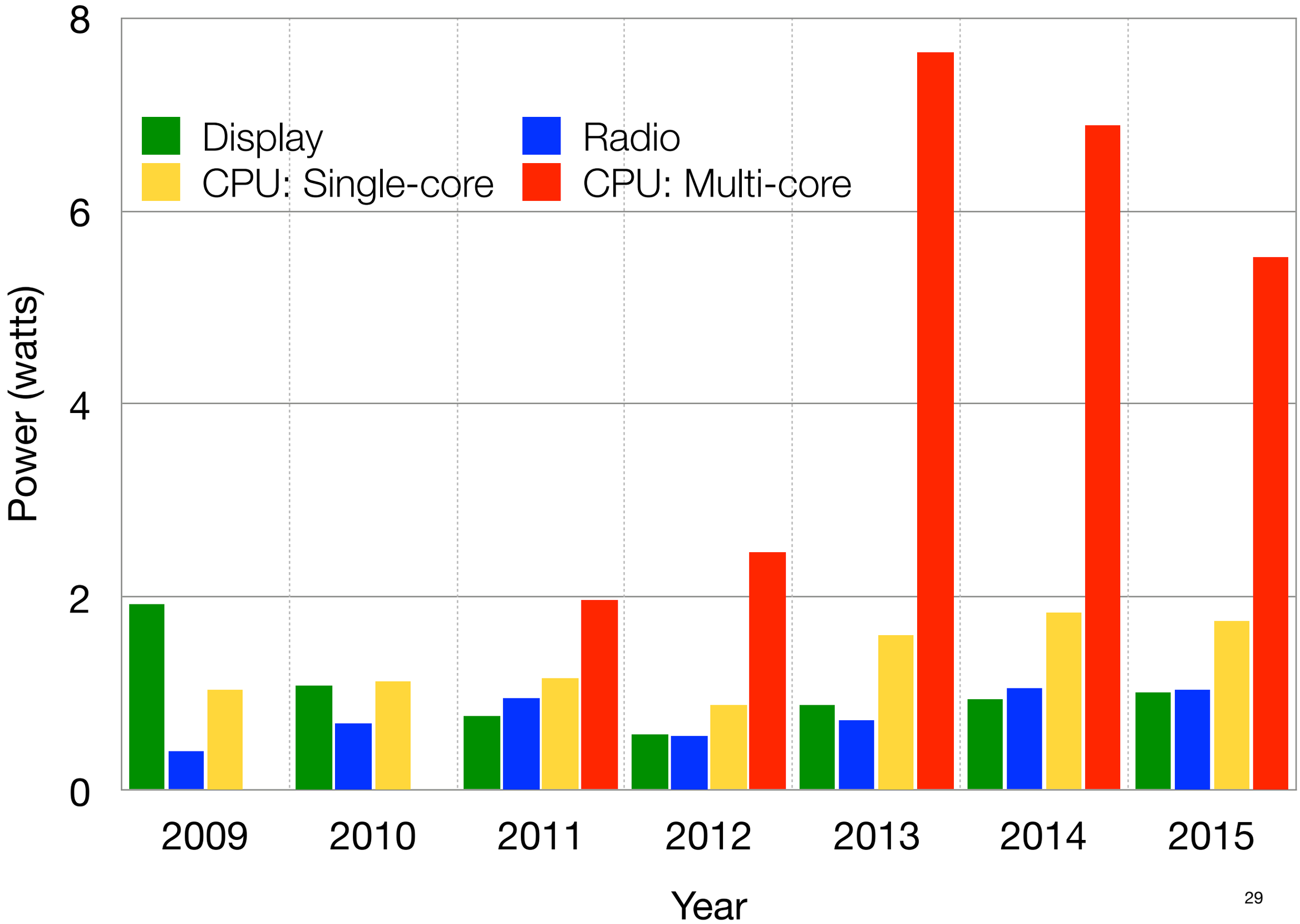

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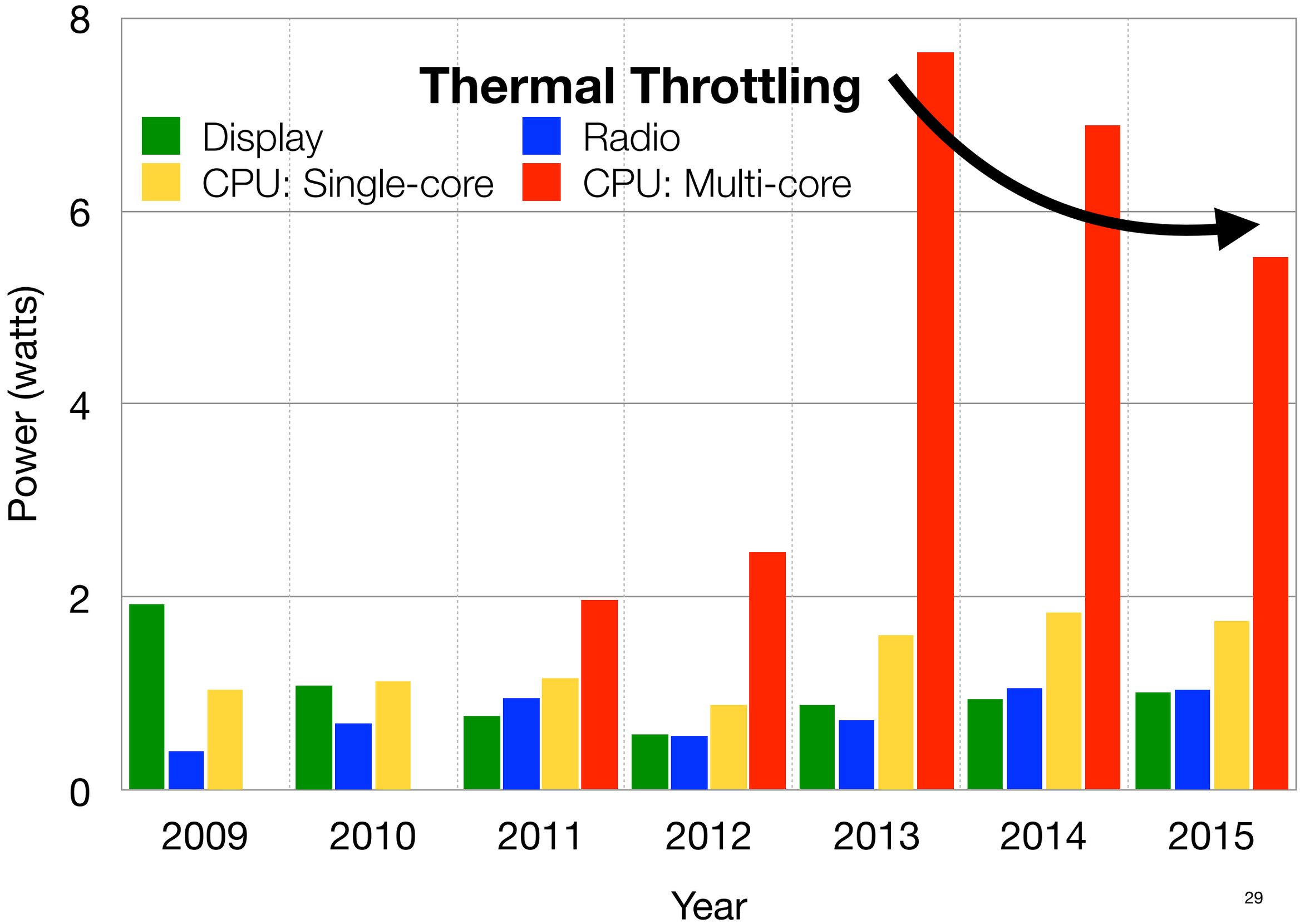

Mobile SoC: Unsustainable By Design

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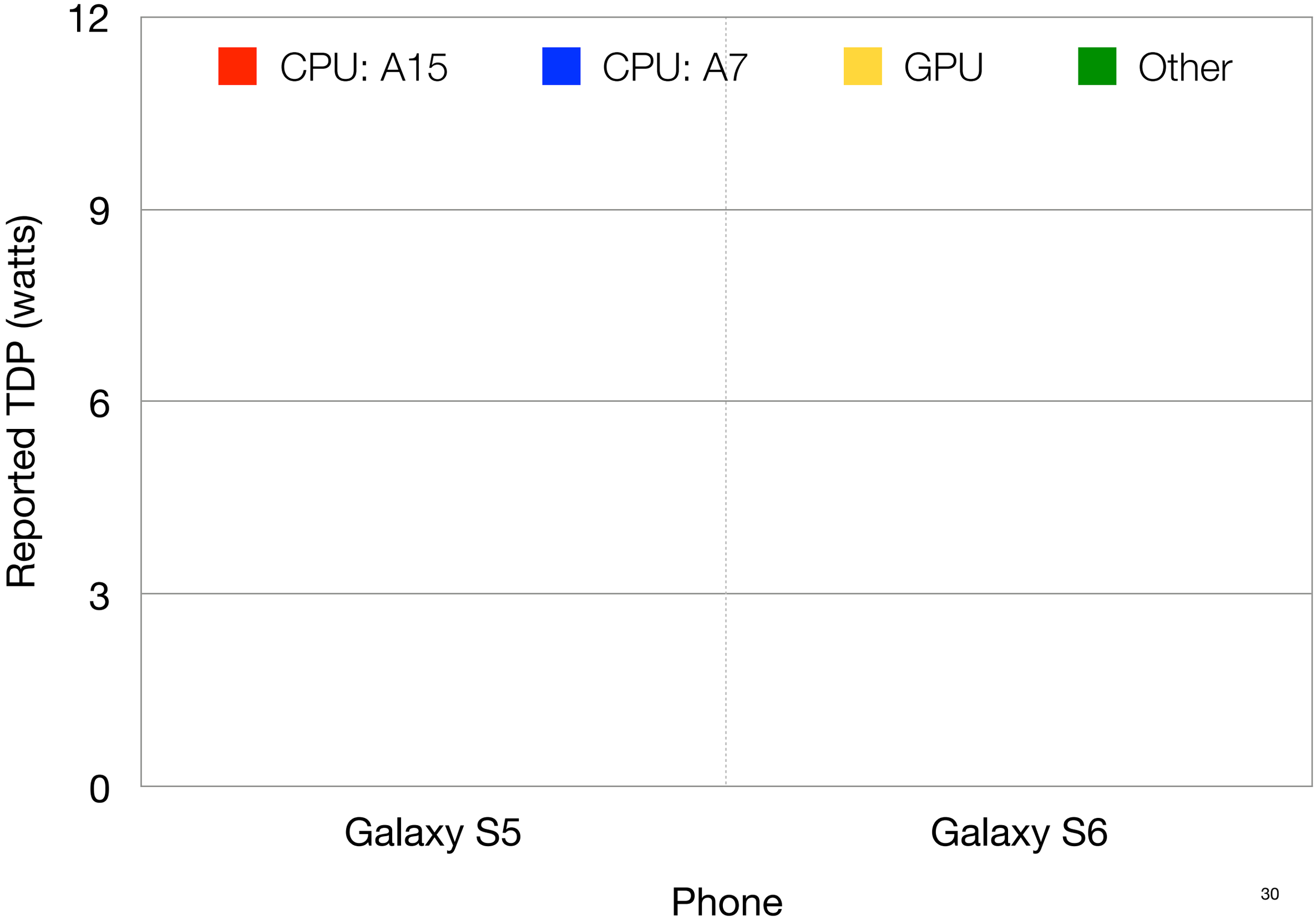

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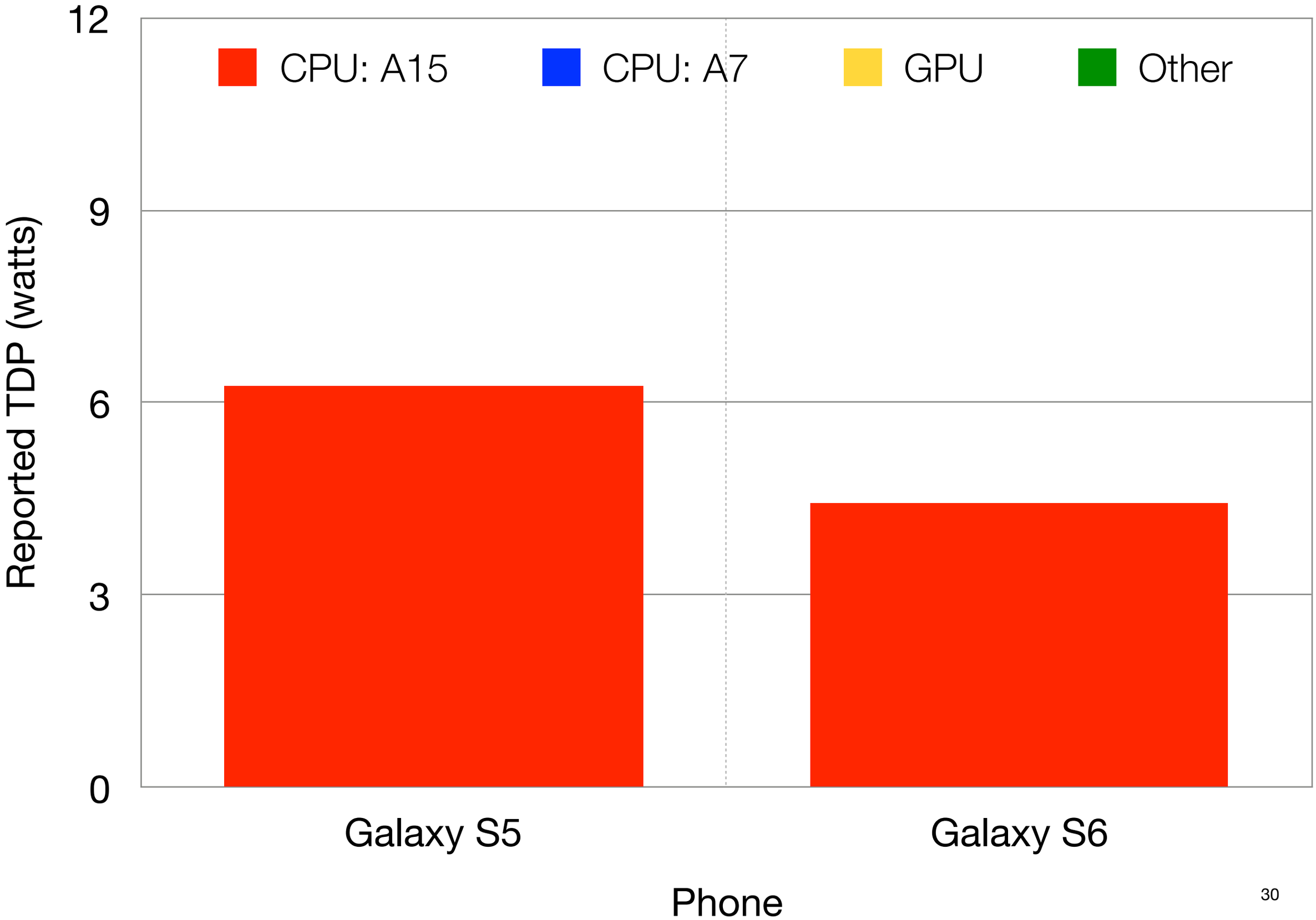

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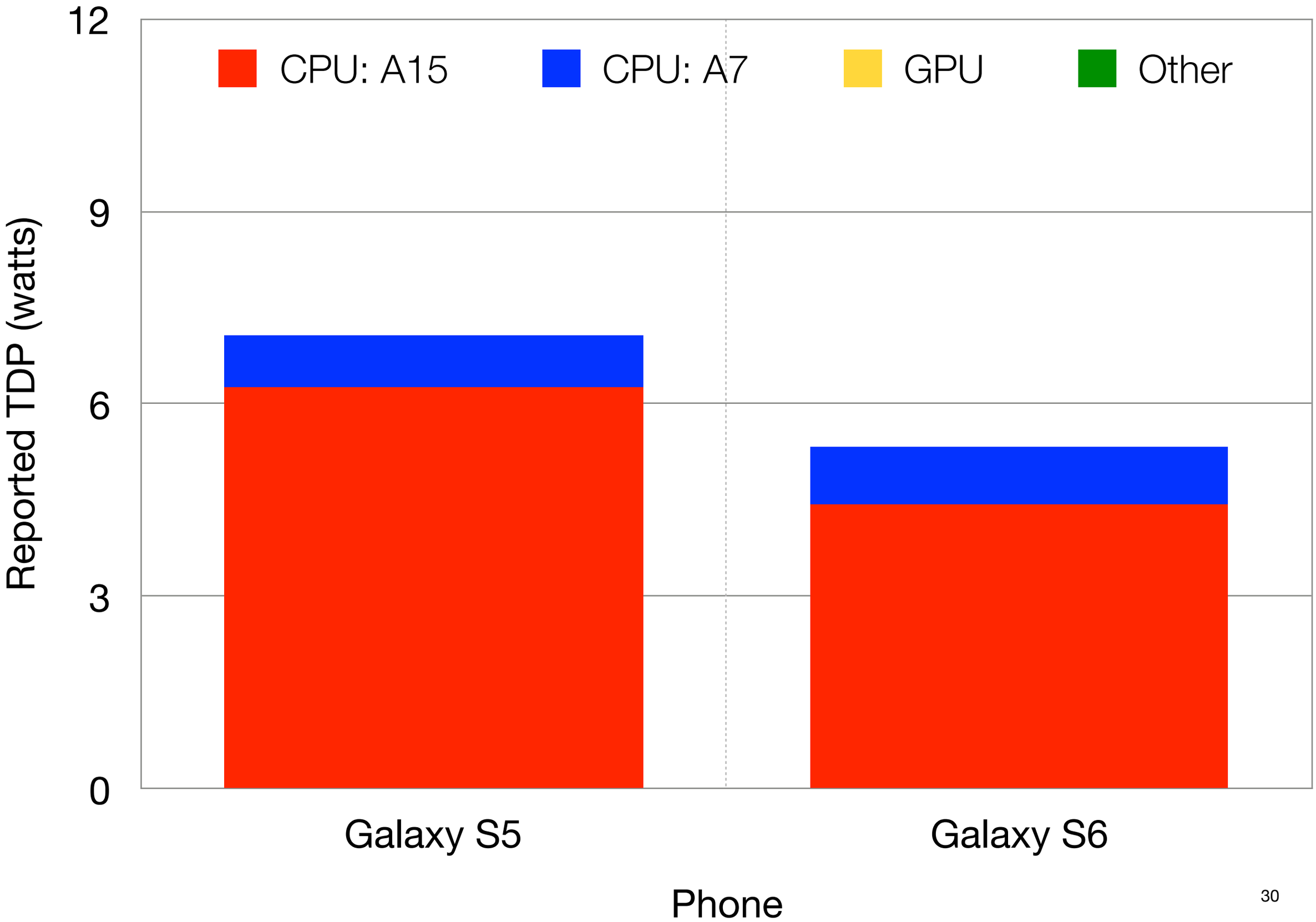

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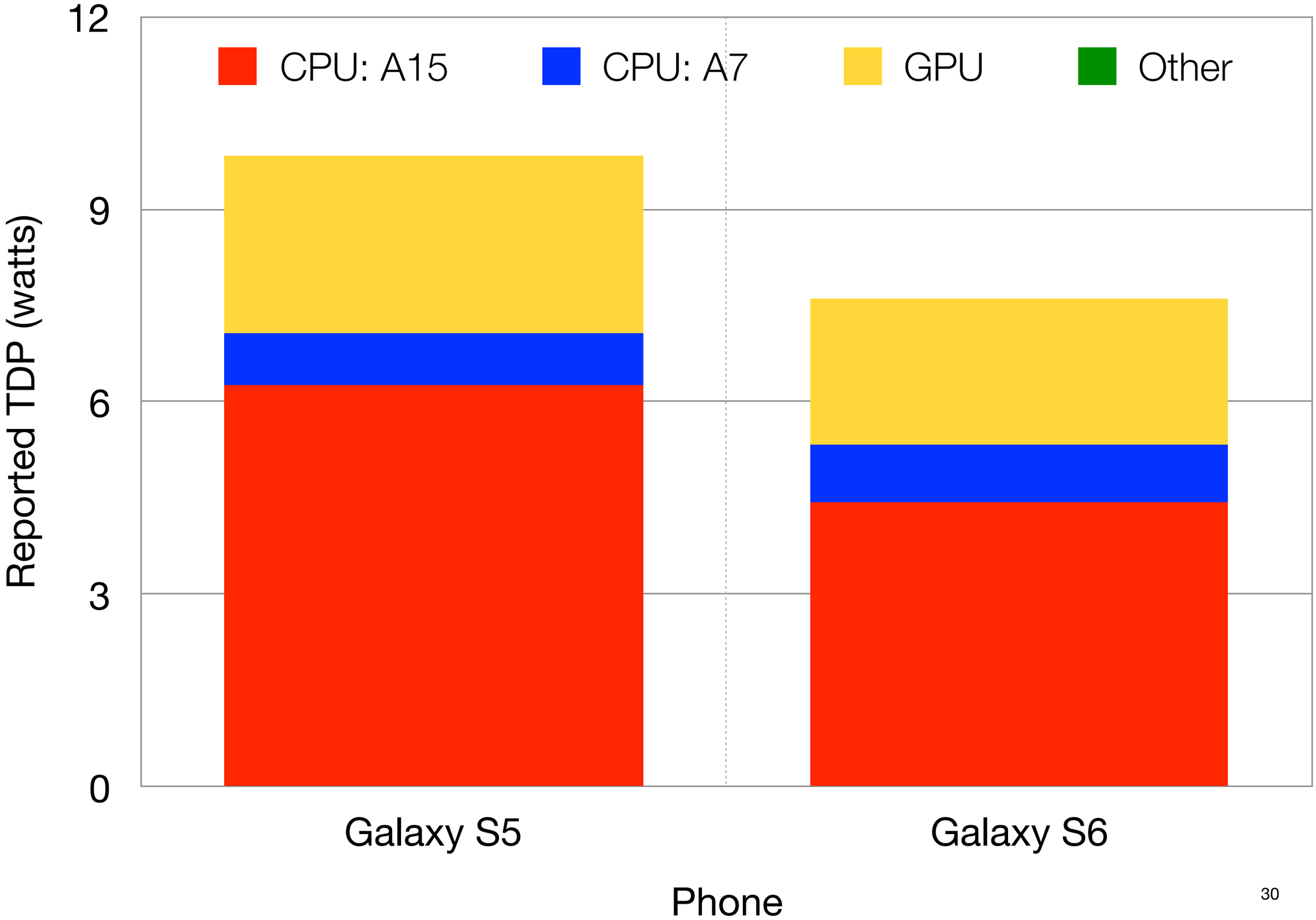

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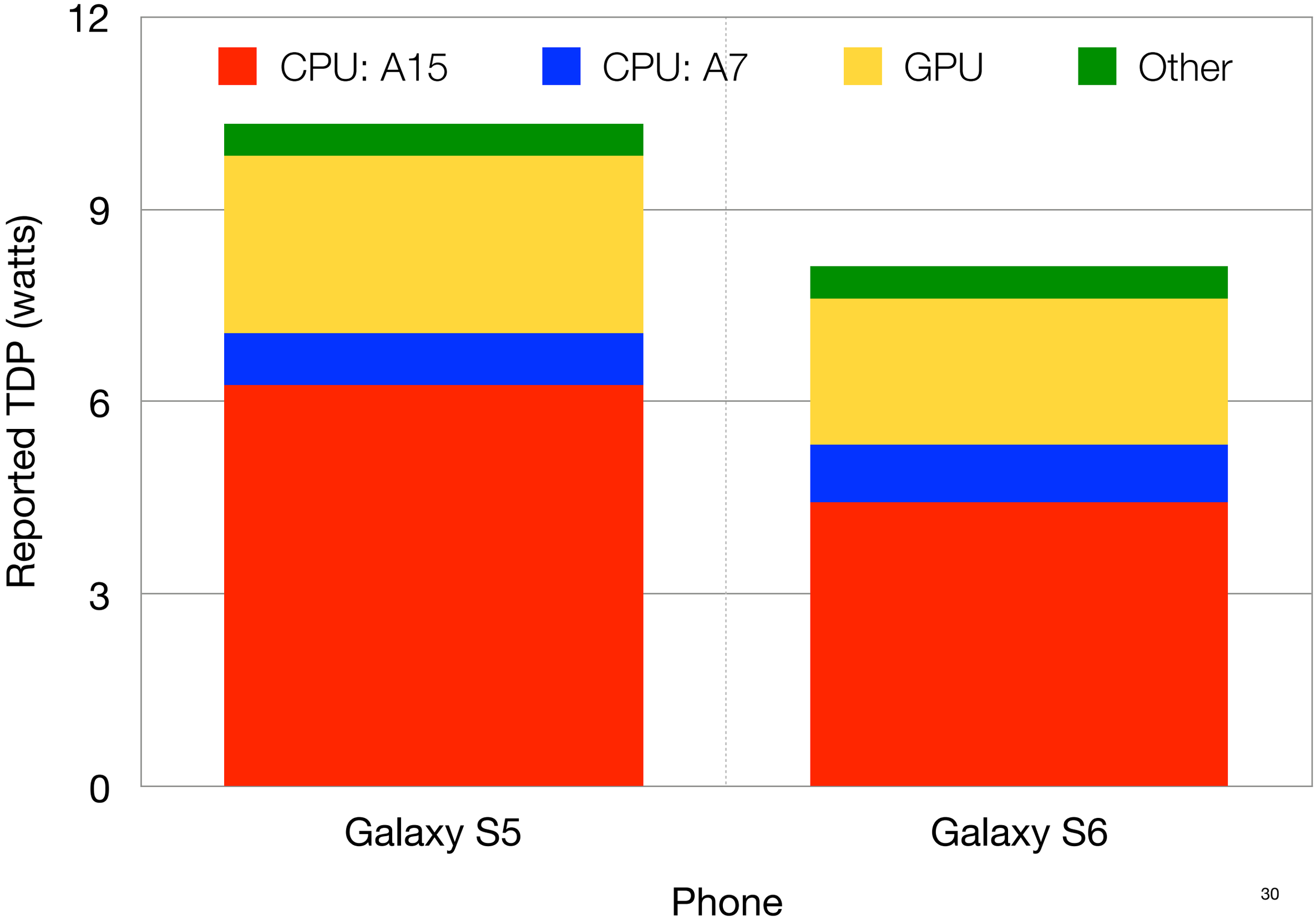

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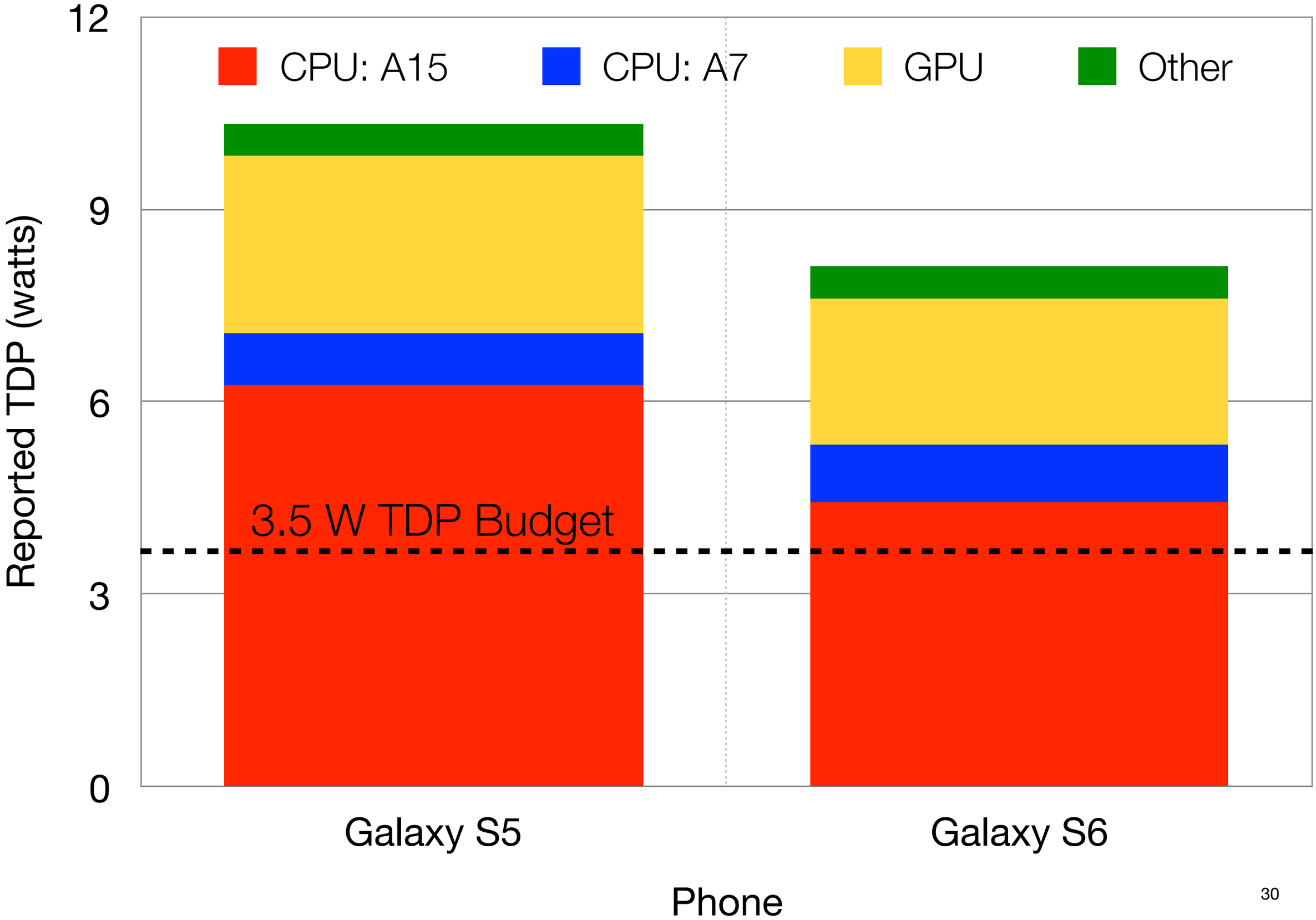
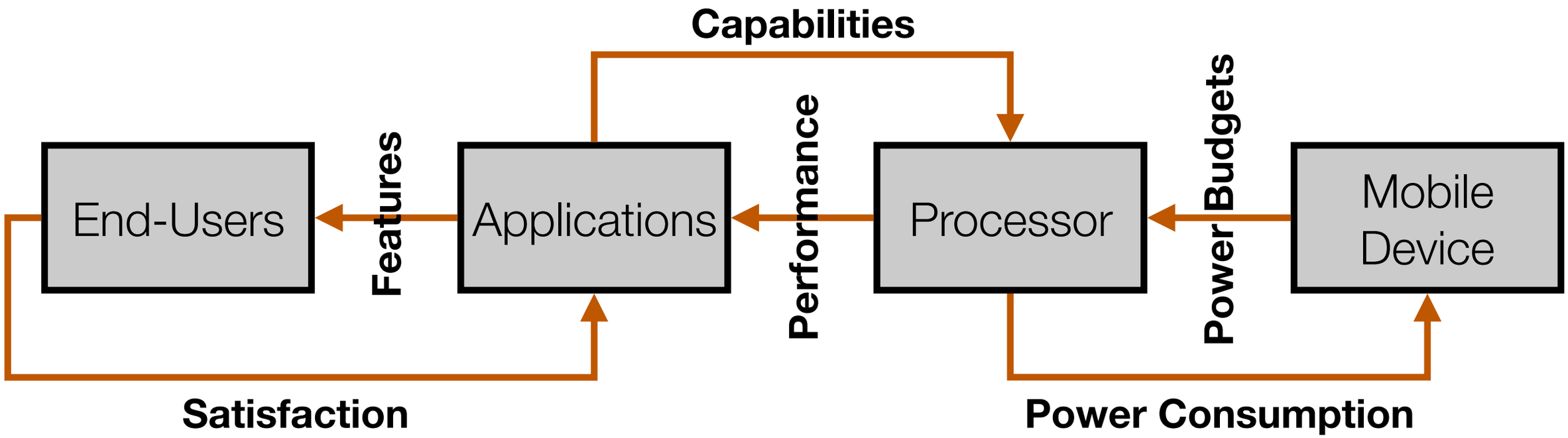


Tying It All Together



A Call to Action

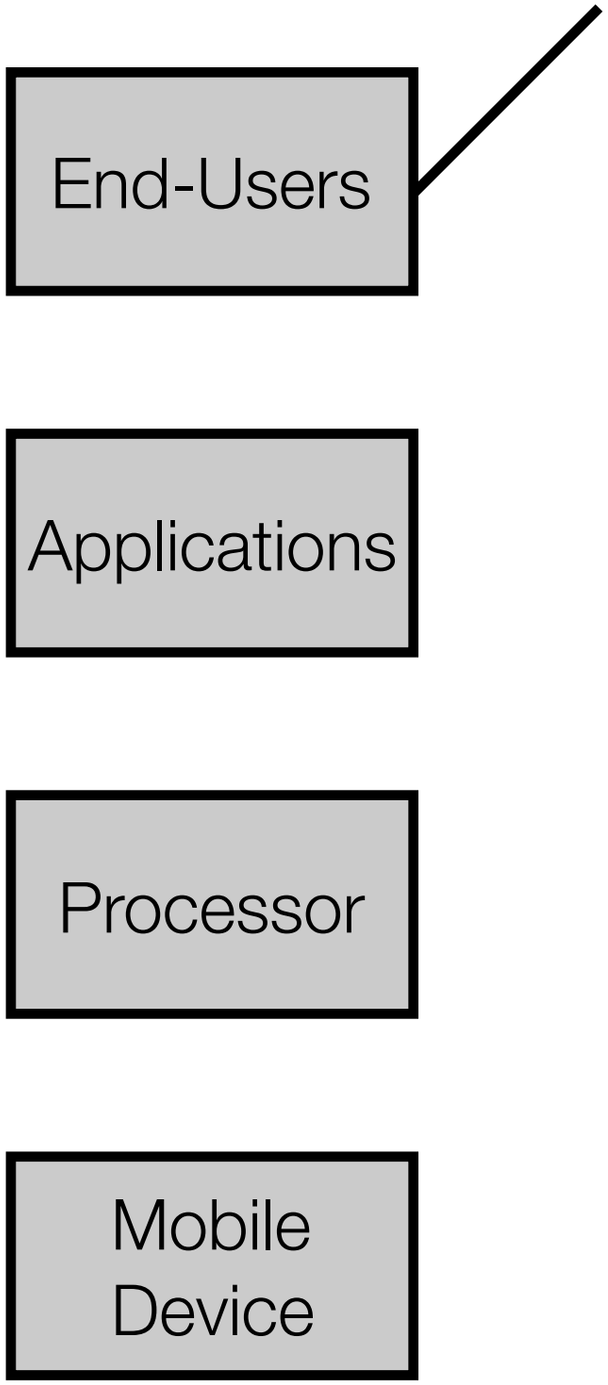
End-Users

Applications

Processor

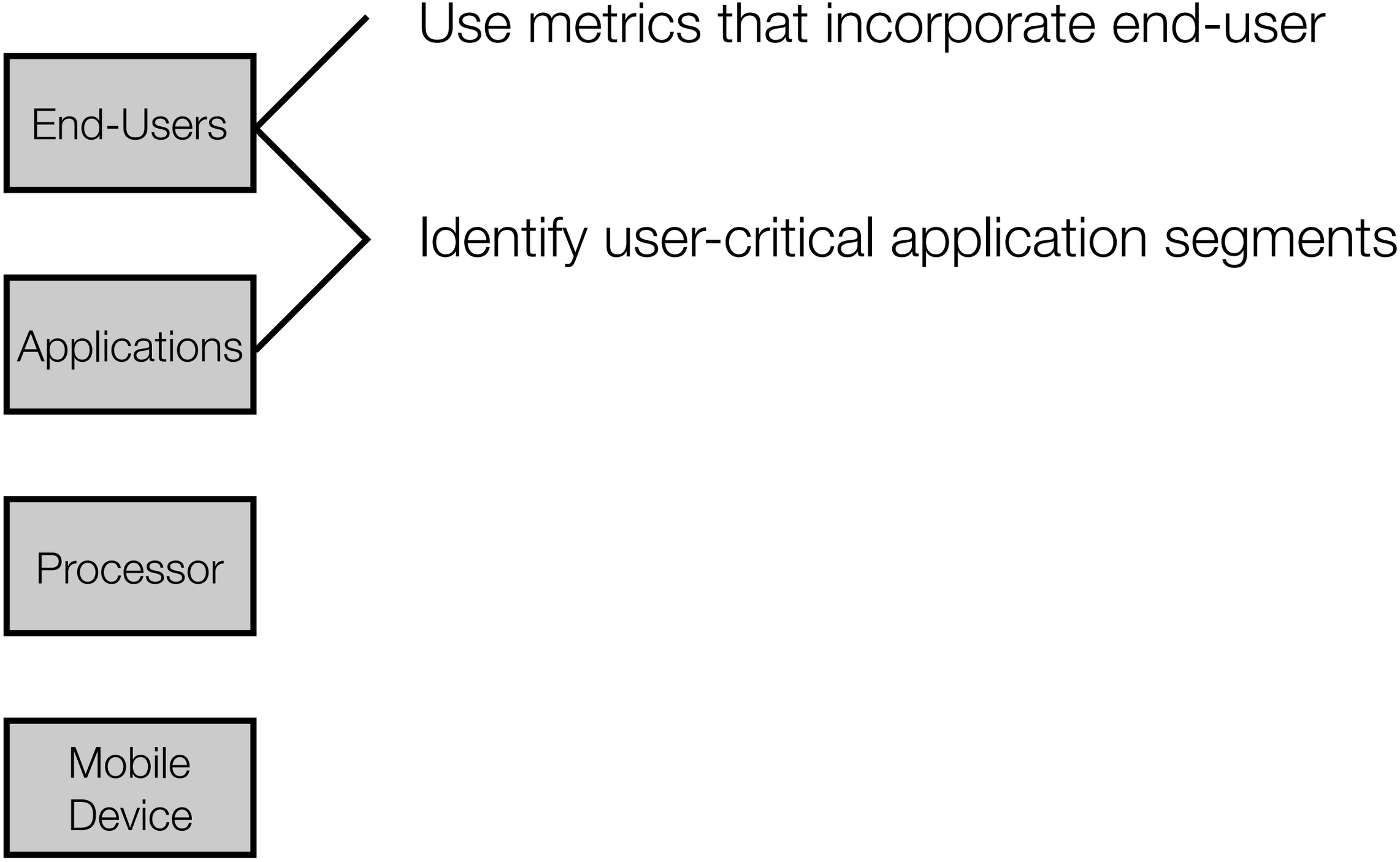
Mobile Device

A Call to Action



Use metrics that incorporate end-user

A Call to Action



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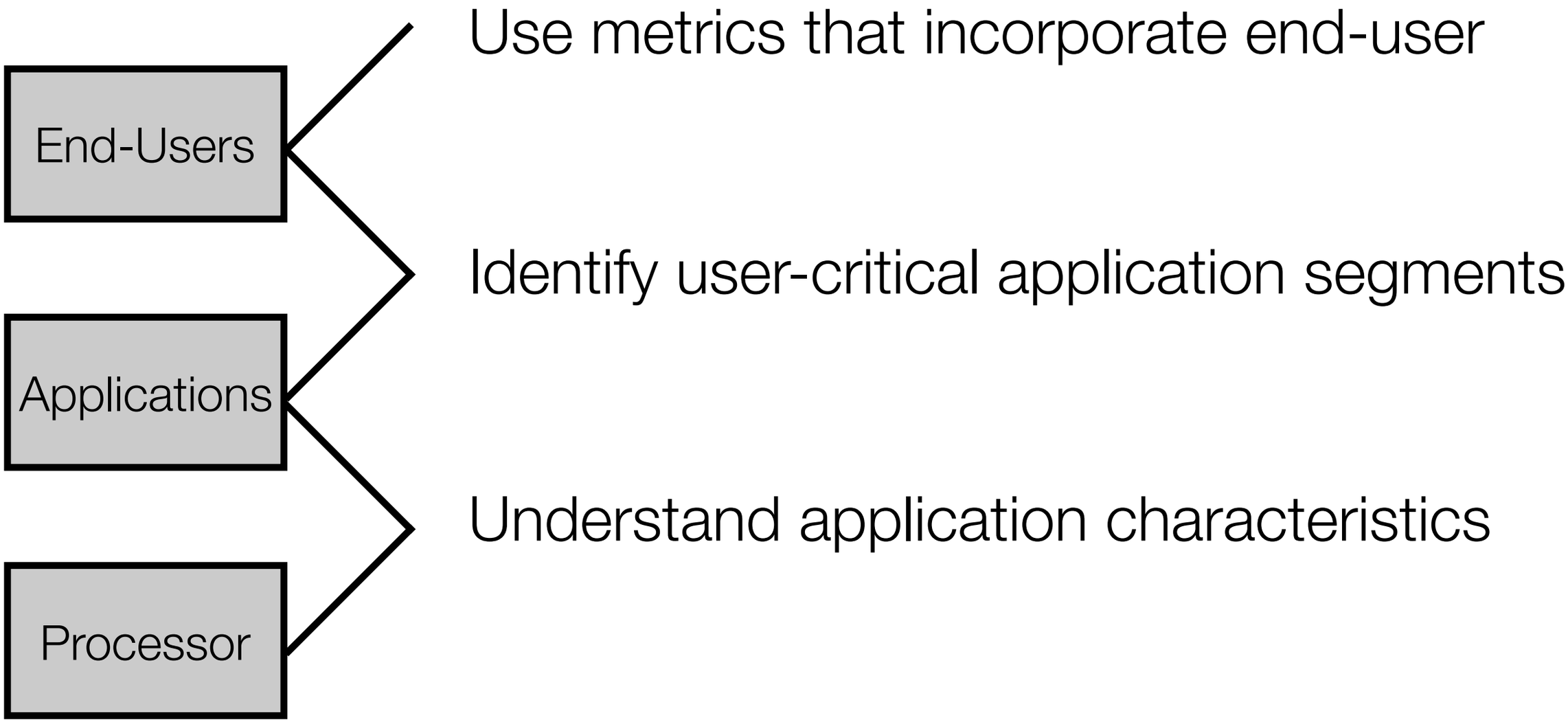

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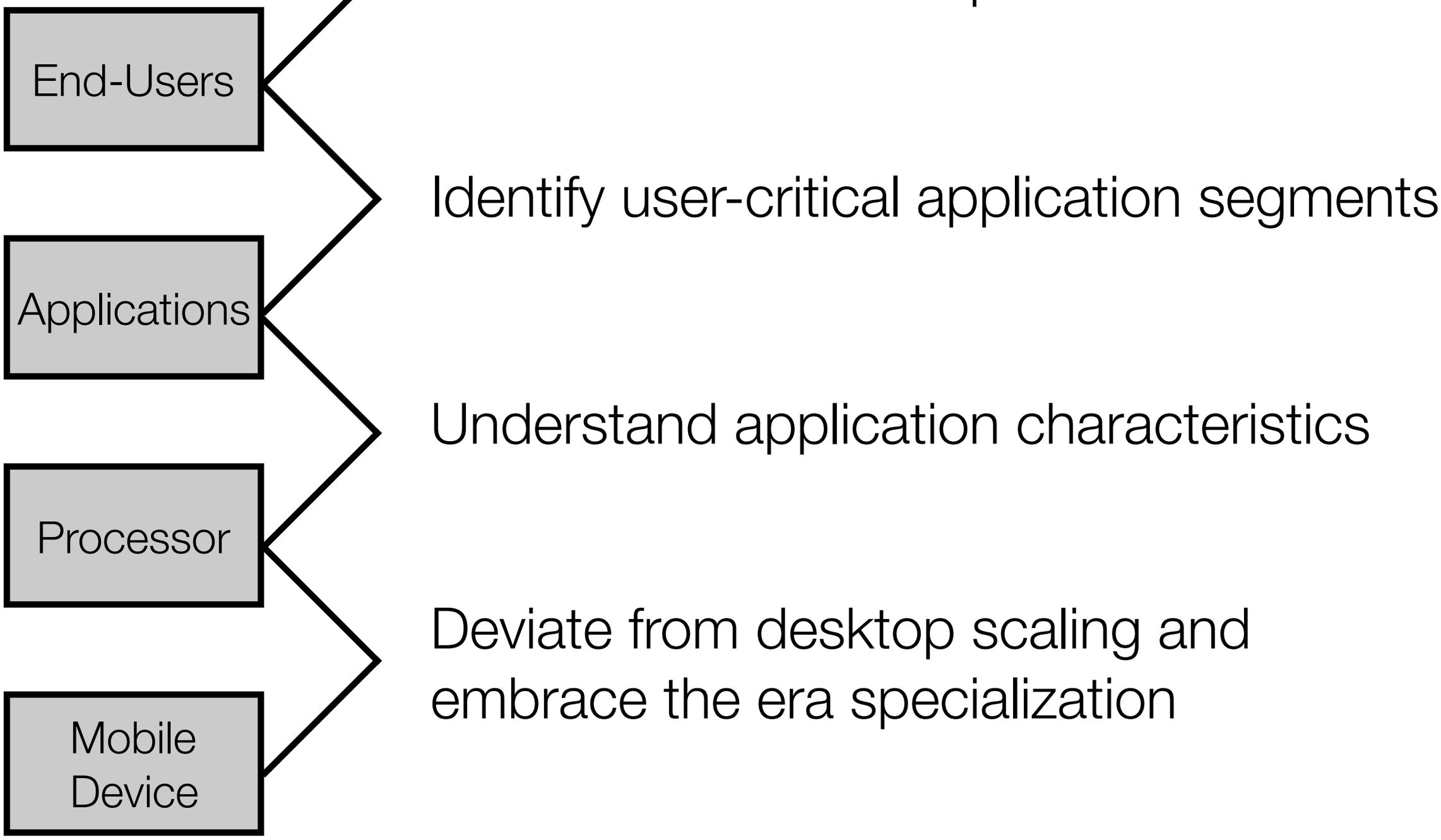

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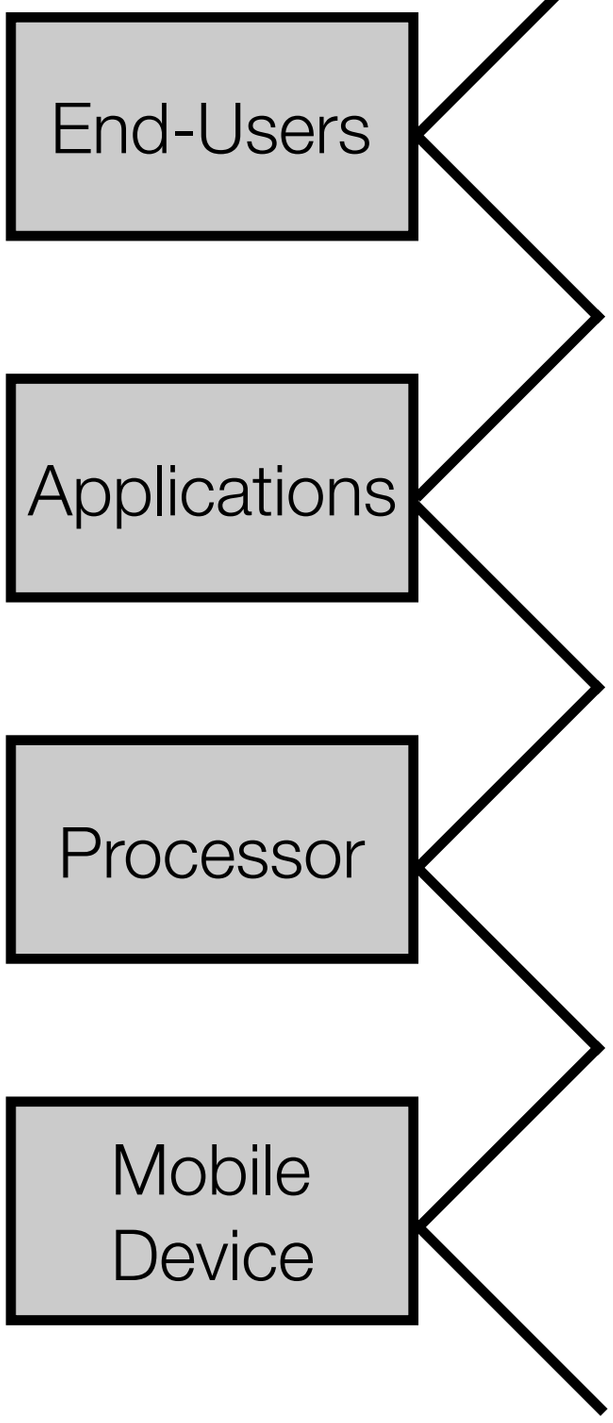


Use metrics that incorporate end-user

Identify user-critical application segments

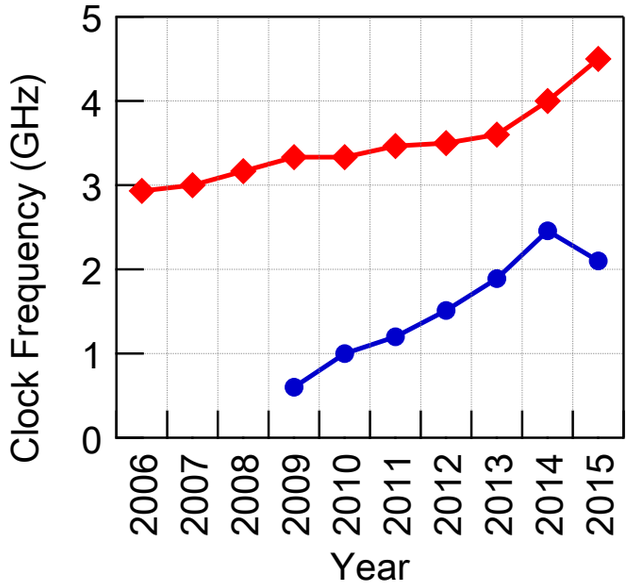
Understand application characteristics

Deviate from desktop scaling and embrace the era specialization

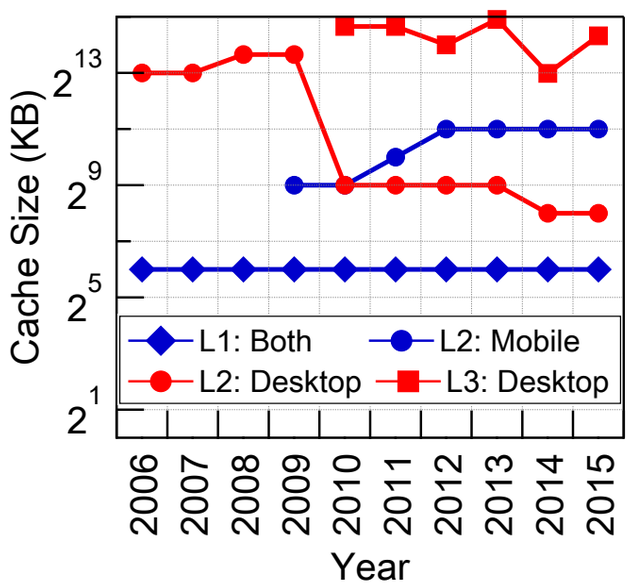
Consider thermal and energy constraints at the mobile-device level

Thank You!

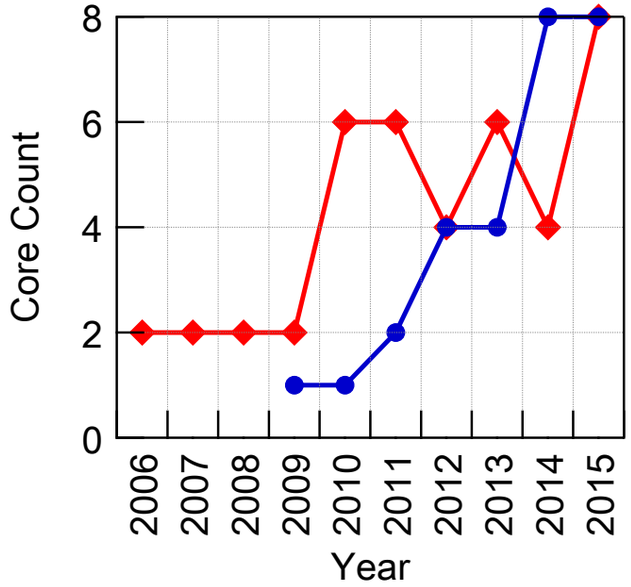
Desktop-like CPU Scaling



Clock Scaling

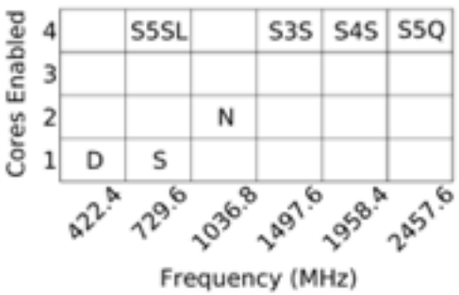


Resource Scaling

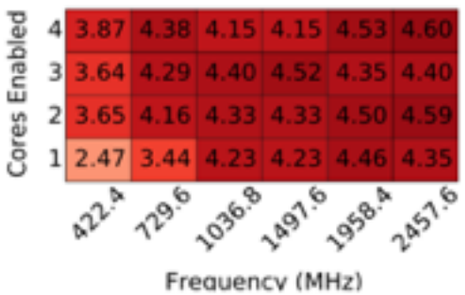


Core Scaling

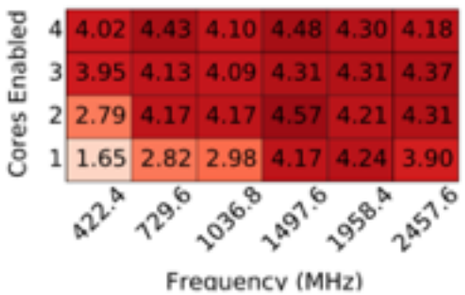
Other Applications



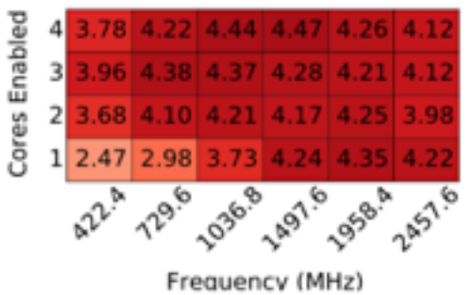
(a) Phone Mapping.



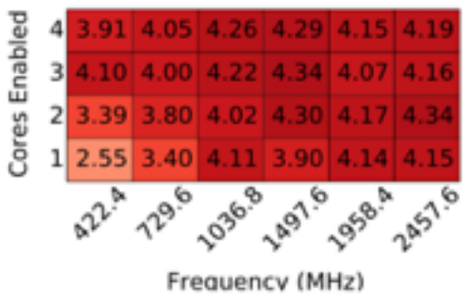
(b) Angry Birds.



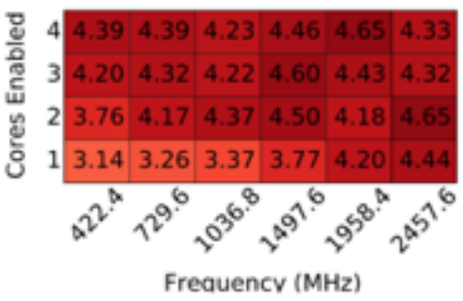
(c) YouTube.



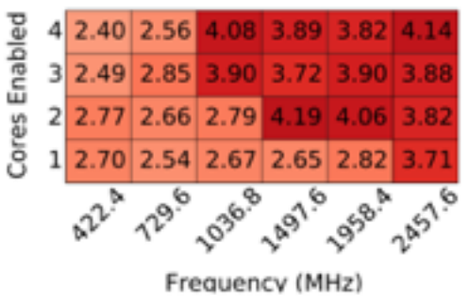
(d) Gladiator.



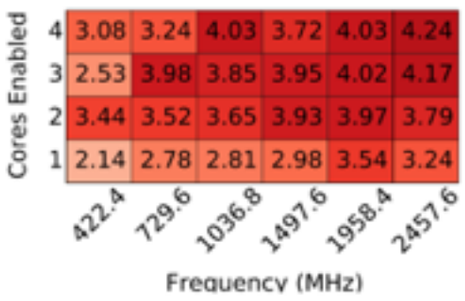
(e) CNN (Chrome).



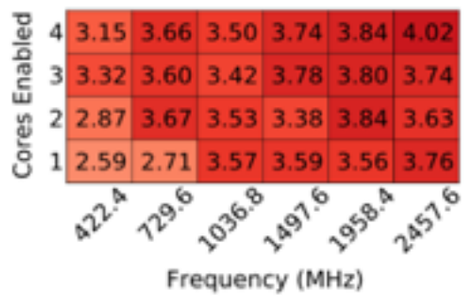
(f) Epic Citadel.



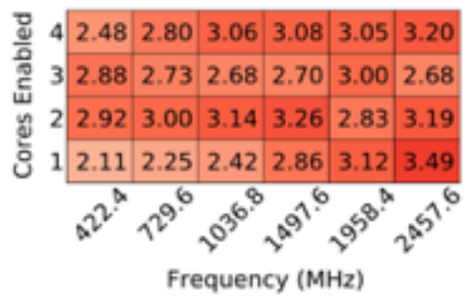
(g) Facebook.



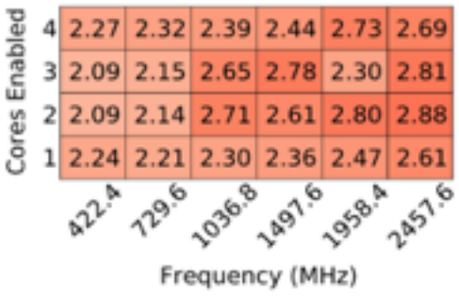
(h) Photoshop Express.

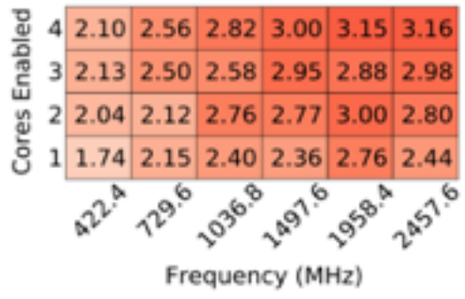


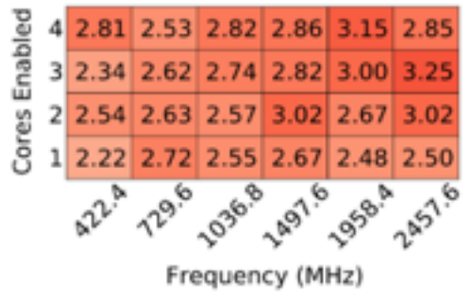
(i) Particles.

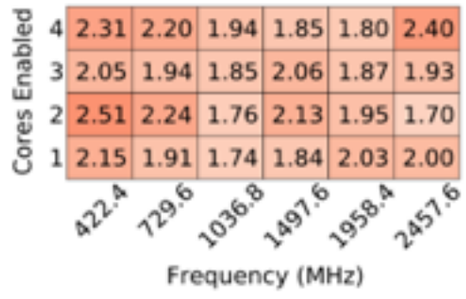


(j) Histogram.









1 - Very Dissatisfied
2 - Dissatisfied
3 - Neutral
4 - Satisfied
5 - Very Satisfied

Application Selection Criteria

	Application Description		User-level Metrics			Computational Metrics (TLP)				
	Name	Description	Installs	Duration	Events	1	2	3	4	Avg
Current-Gen	Angry Birds	Navigate to and play first level	0.5-1E9	0:41	6	21%	8%	2%	0%	1.43
	CNN (Chrome)	Navigate to and scroll through CNN.com	1-5E8	0:36	12	16%	11%	7%	2%	1.90
	Epic Citadel	Navigate through environment	0.5-1E6	0:44	15	25%	22%	5%	0%	1.67
	Facebook	Log-in and visit ESPN brand page	0.5-1E9	0:57	23	16%	8%	3%	1%	1.67
	Gladiator	Sword-fight opponent in first level	1-5E6	0:36	31	31%	8%	2%	0%	1.34
	Photoshop Express	Apply various filters and effects to image	1-5E7	0:48	15	13%	9%	6%	15%	2.52
	Youtube	Navigate to and watch video	1-5E7	0:46	13	16%	10%	5%	1%	1.73
Next-Gen	Ambiant Occlusion	Brute force ray primitive intersection	1-5E3	0:21	4	7%	3%	2%	46%	3.46
	Face Detection	Face detection on video	1-5E3	0:21	3	17%	4%	2%	47%	3.09
	Gaussian Blur	Guassian Blur on video	1-5E3	0:21	3	51%	4%	2%	4%	1.37
	Julia	Visualization of Julia Set dynamics	1-5E3	0:17	4	11%	4%	2%	24%	2.93
	Particles	Particle simulation in a spatial grid	1-5E3	0:21	4	17%	14%	14%	7%	2.21

Apple SoCs

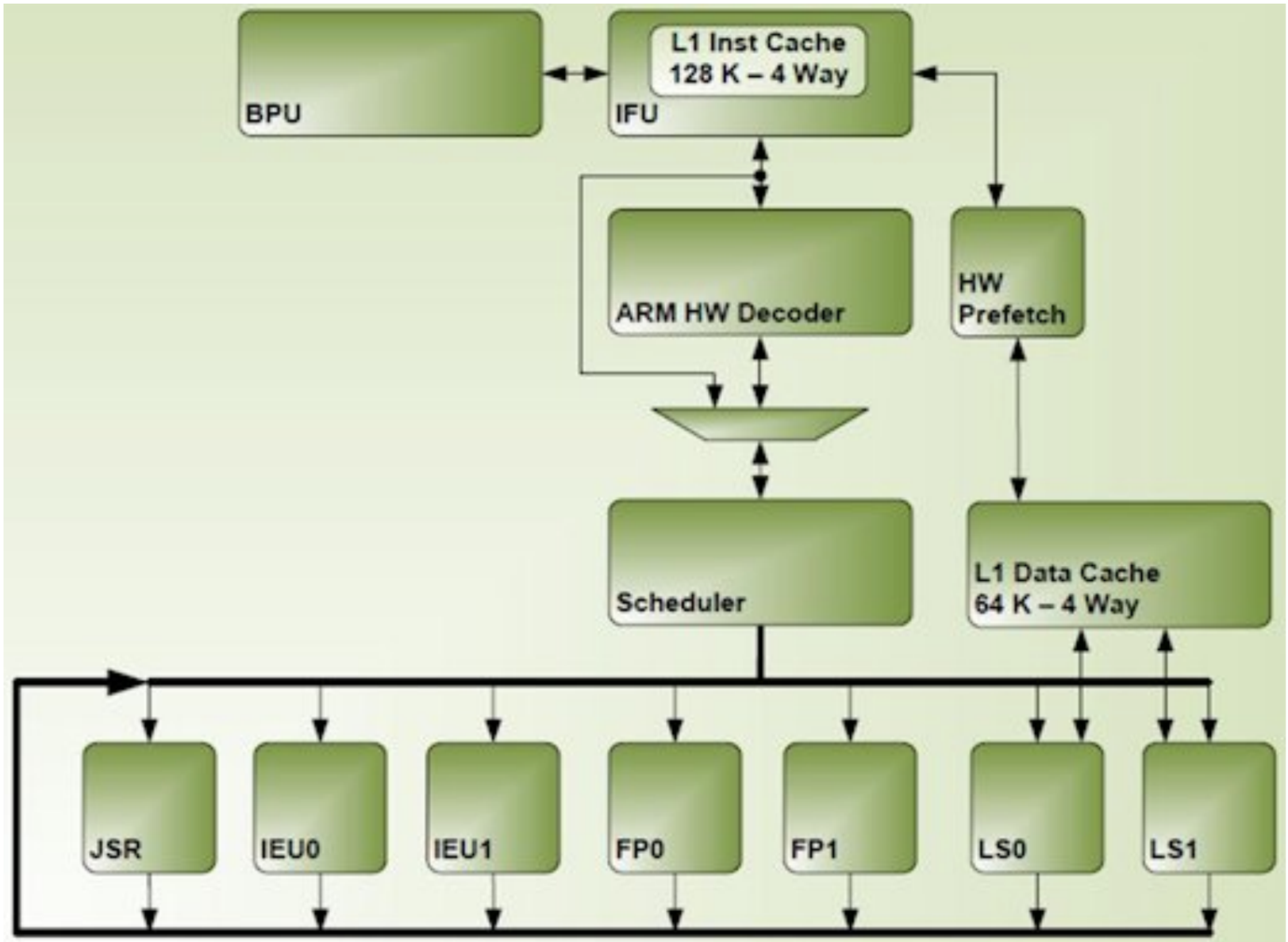
Apple SoC Comparison				
	A9X	**A9**	**A8X**	**A6X**
CPU	2x Twister	2x Twister	3x Typhoon	2x Swift
CPU Clockspeed	2.26GHz	1.85GHz	1.5GHz	1.3GHz
GPU	PVR 10 cluster Series7?	PVR GT7600	Apple/PVR GXA6850	PVR SGX554 MP4
RAM	4GB LPDDR4	2GB LPDDR4	2GB LPDDR3	1GB LPDDR2
Memory Bus Width	128-bit	64-bit	128-bit	128-bit
Memory Bandwidth	51.2GB/sec	25.6GB/sec	25.6GB/sec	17.1GB/sec
L2 Cache	3MB	3MB	2MB	1MB
Manufacturing Process	Unknown (TSMC 16nm or Samsung 14nm)	TSMC 16nm & Samsung 14nm	TSMC 20nm	Samsung 32nm

http://www.anandtech.com/show/9780/taking-notes-with-ipad-pro/2

Apple CPUs

Apple Custom CPU Core Comparison		
	Apple A8	**Apple A9**
CPU Codename	Typhoon	Twister
ARM ISA	ARMv8-A (32/64-bit)	ARMv8-A (32/64-bit)
Issue Width	6 micro-ops	6 micro-ops
Reorder Buffer Size	192 micro-ops	192 micro-ops
Branch Mispredict Penalty	16 (14 - 19)	9
Integer ALUs	4	4
Shifter ALUs	2	4
Load/Store Units	2	2
Addition (FP32) Latency	4 cycles	3 cycles
Multiplication (FP32) Latency	5 cycles	4 cycles
Addition (INT) Latency	1 cycle	1 cycle
Multiplication (INT) Latency	3 cycles	3 cycles
Branch Units	2	2
Indirect Branch Units	1	1
FP/NEON ALUs	3 (3 Add or 2 Mult)	3 (3 Add or 3 Mult)
L1 Cache	64KB I$ + 64KB D$	64KB I$ + 64KB D$
L2 Cache	1MB	3MB
L3 Cache	4MB	~~8MB~~ 4MB

http://www.anandtech.com/show/9686/the-apple-iphone-6s-and-iphone-6s-plus-review/4



http://techreport.com/r.x/2014_8_11_Nvidia_claims_Haswellclass_performance_for_Denver_CPU_core/denver-block.jpg

Crowdsourcing Considerations

Crowdsourcing Considerations

1. Thank you for participating in our smartphone user experience study. The clip shown above is an application usage scenario recorded on an Android smartphone. As a user of the application, how satisfied are you with the smartphone's performance (i.e., application responsiveness and fluidness)?

- 5 - Very Satisfied
- 4 - Satisfied
- 3 - Neutral
- 2 - Dissatisfied
- 1 - Very Dissatisfied

2. Please enter a random word below to use as your survey confirmation code (e.g., a fruit, vegetable, animal, color, appliance, etc.) when returning to the Mechanical Turk HIT page.

Done

Powered by SurveyMonkey
See how easy it is to create a survey.

Crowdsourcing Considerations

Task Design

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- Open-ended question

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Crowdsourcing Considerations

Task Design

- Open-ended question
- Well-defined answers

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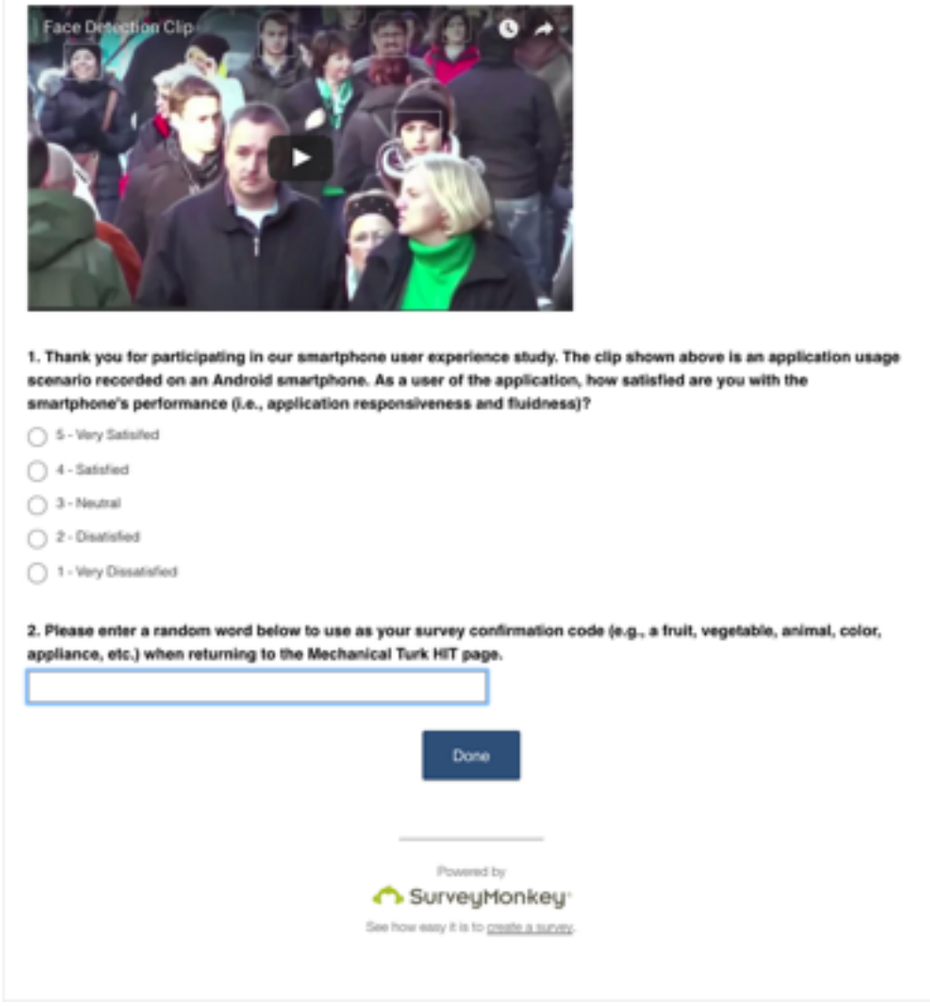
Crowdsourcing Considerations

Task Design

- Open-ended question
- Well-defined answers

Worker Recruitment and Incentive



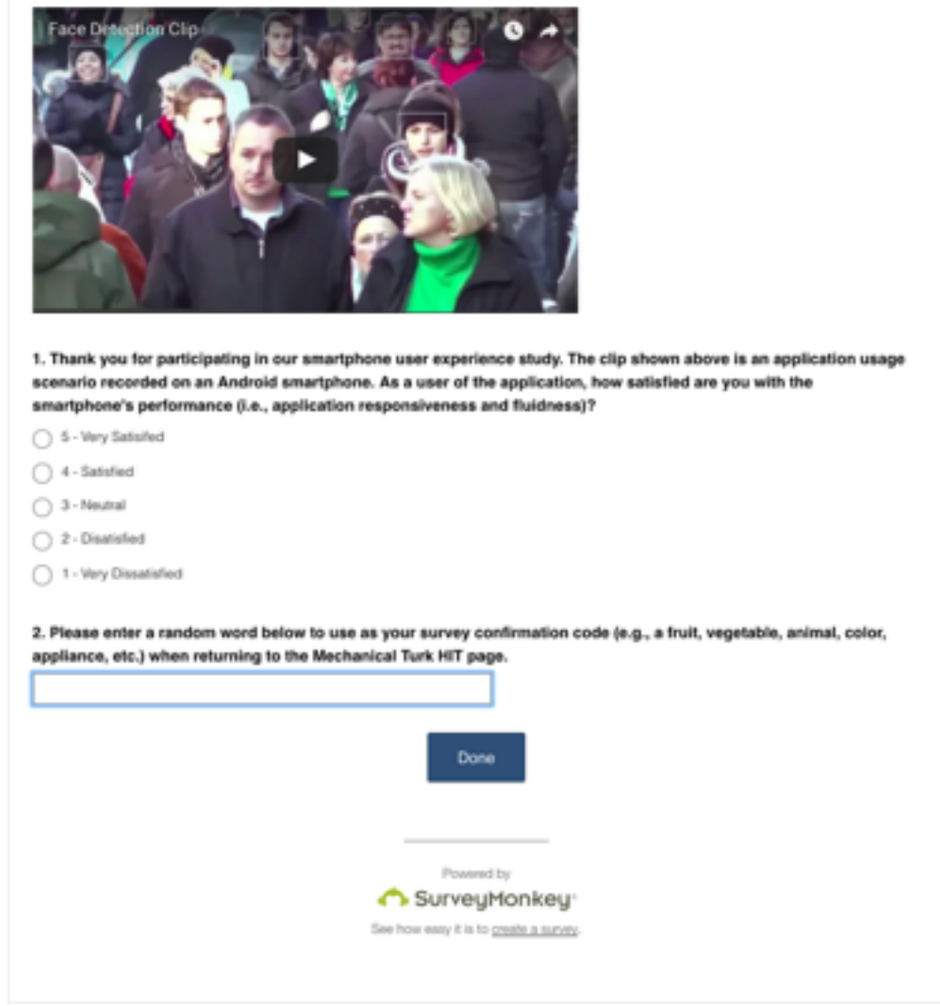
Crowdsourcing Considerations

Task Design

- Open-ended question
- Well-defined answers

Worker Recruitment and Incentive

- $0.10 / task



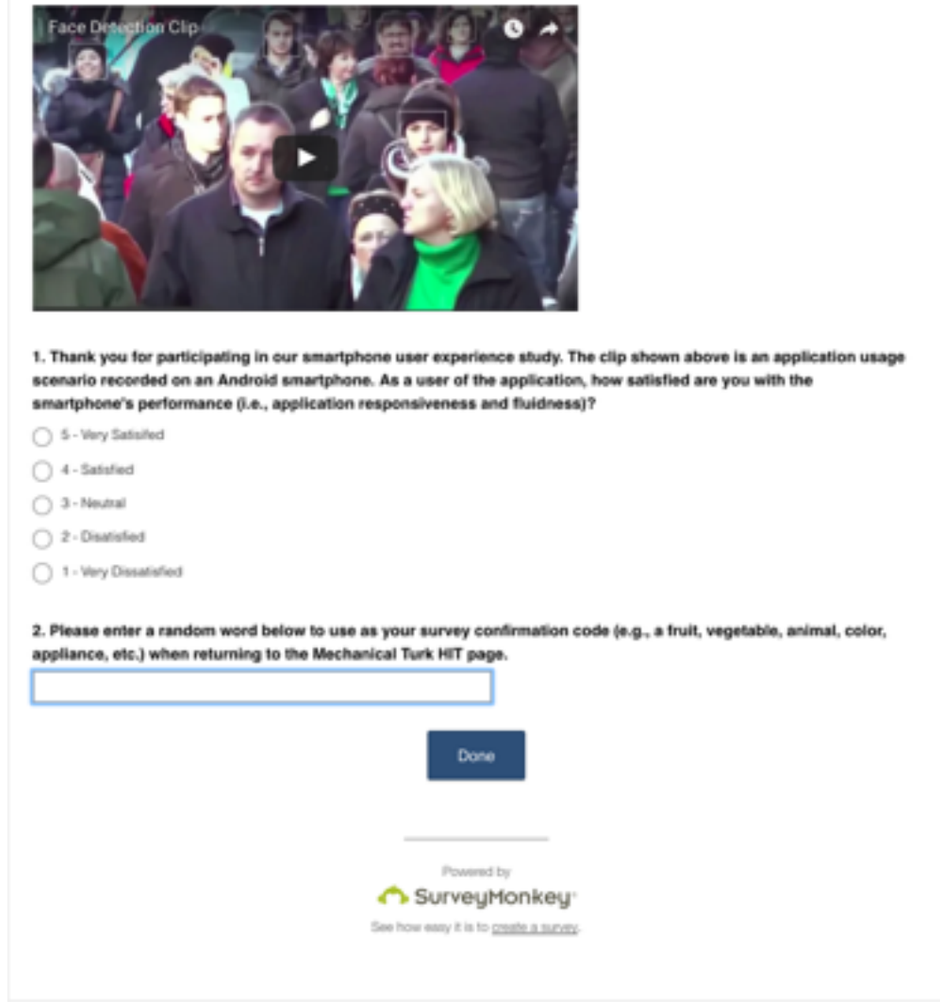
Crowdsourcing Considerations

Task Design

- Open-ended question
- Well-defined answers

Worker Recruitment and Incentive

- $0.10 / task
- $8.00 / hour wage



Crowdsourcing Considerations

Task Design

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- Well-defined answers

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Data Integrity

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Crowdsourcing Considerations

Task Design

- Open-ended question
- Well-defined answers

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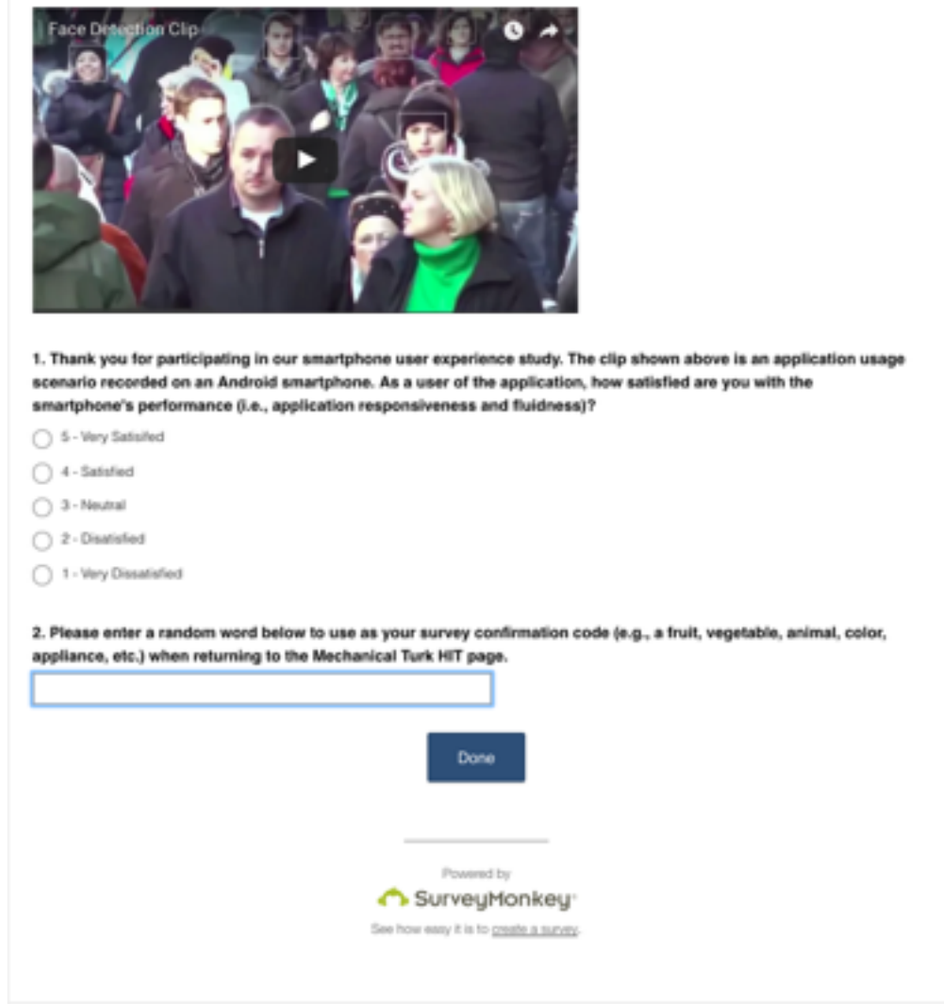
- $8.00 / hour wage

Data Integrity

- Scale of trials (> 50 trials / configuration)



Crowdsourcing Considerations

Task Design

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- Well-defined answers

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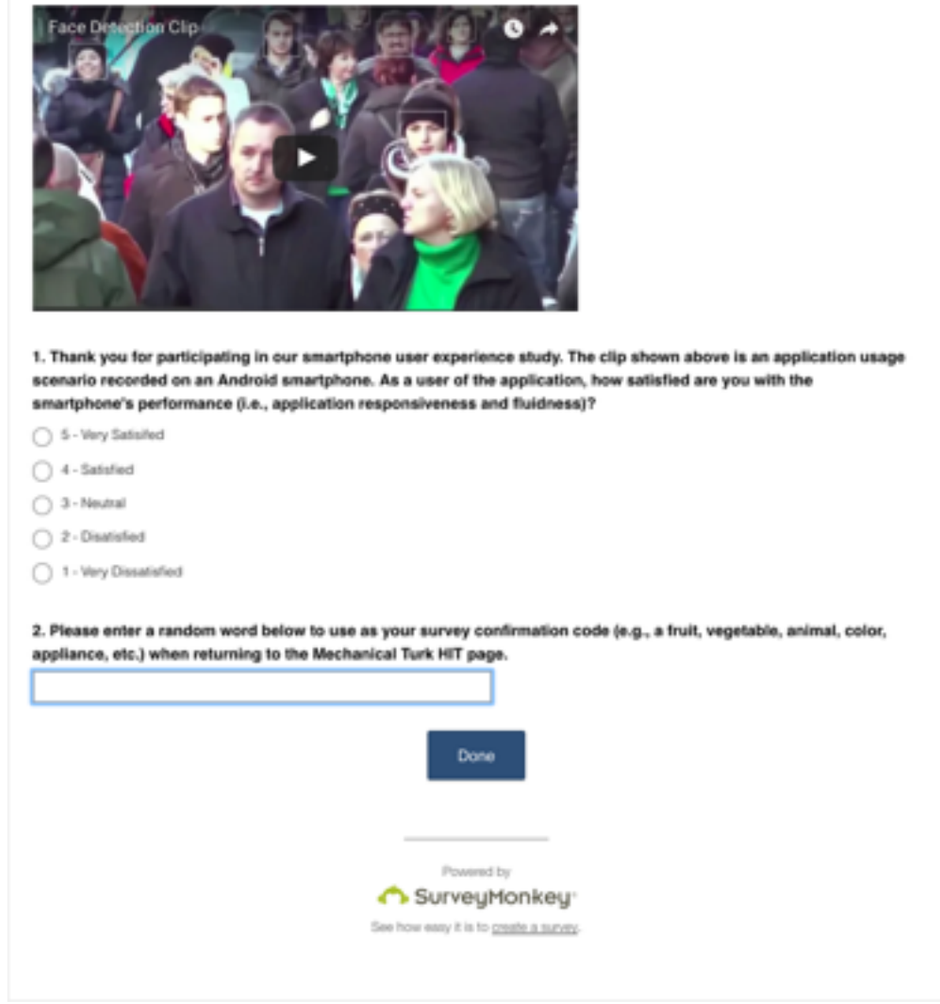
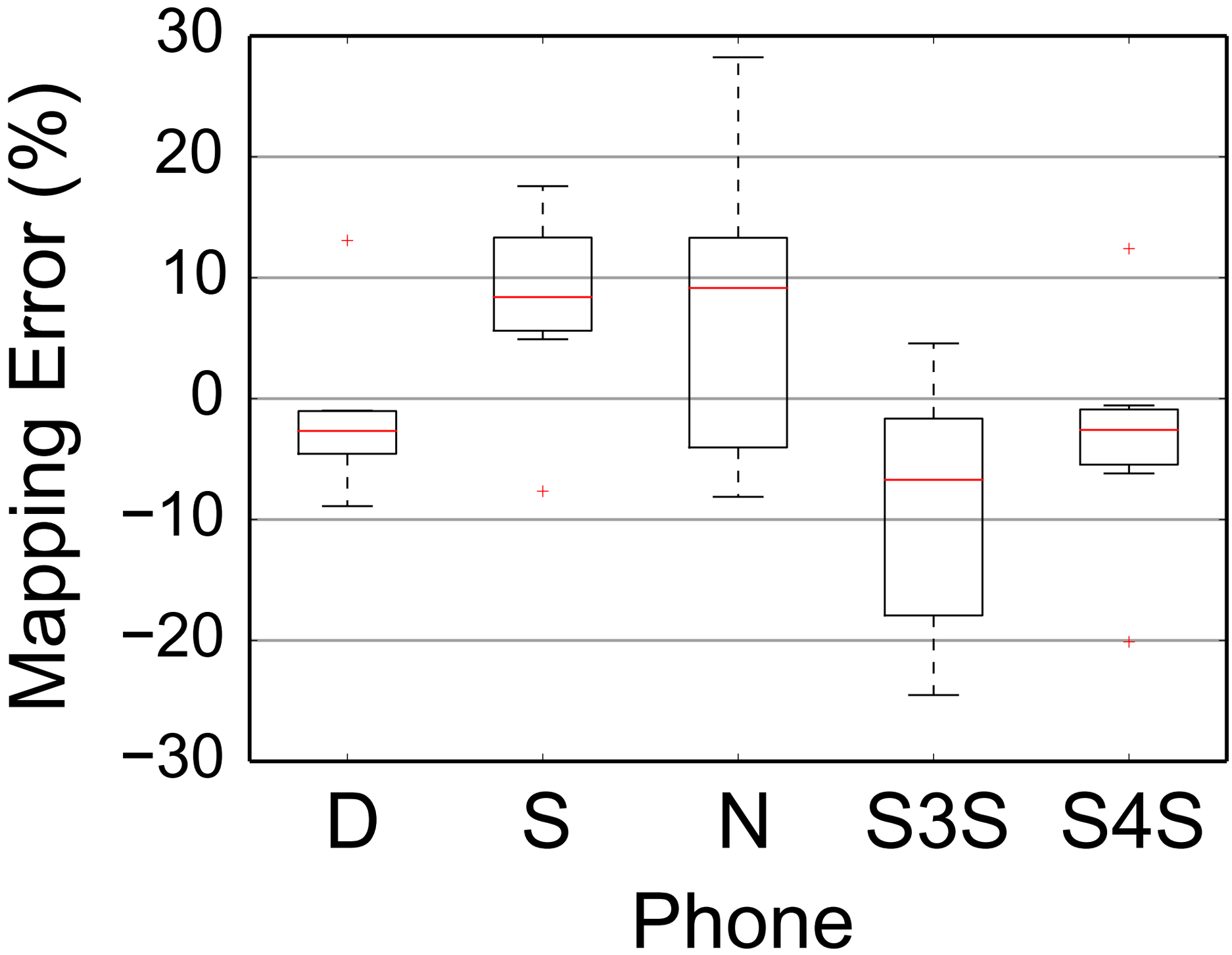
Data Integrity

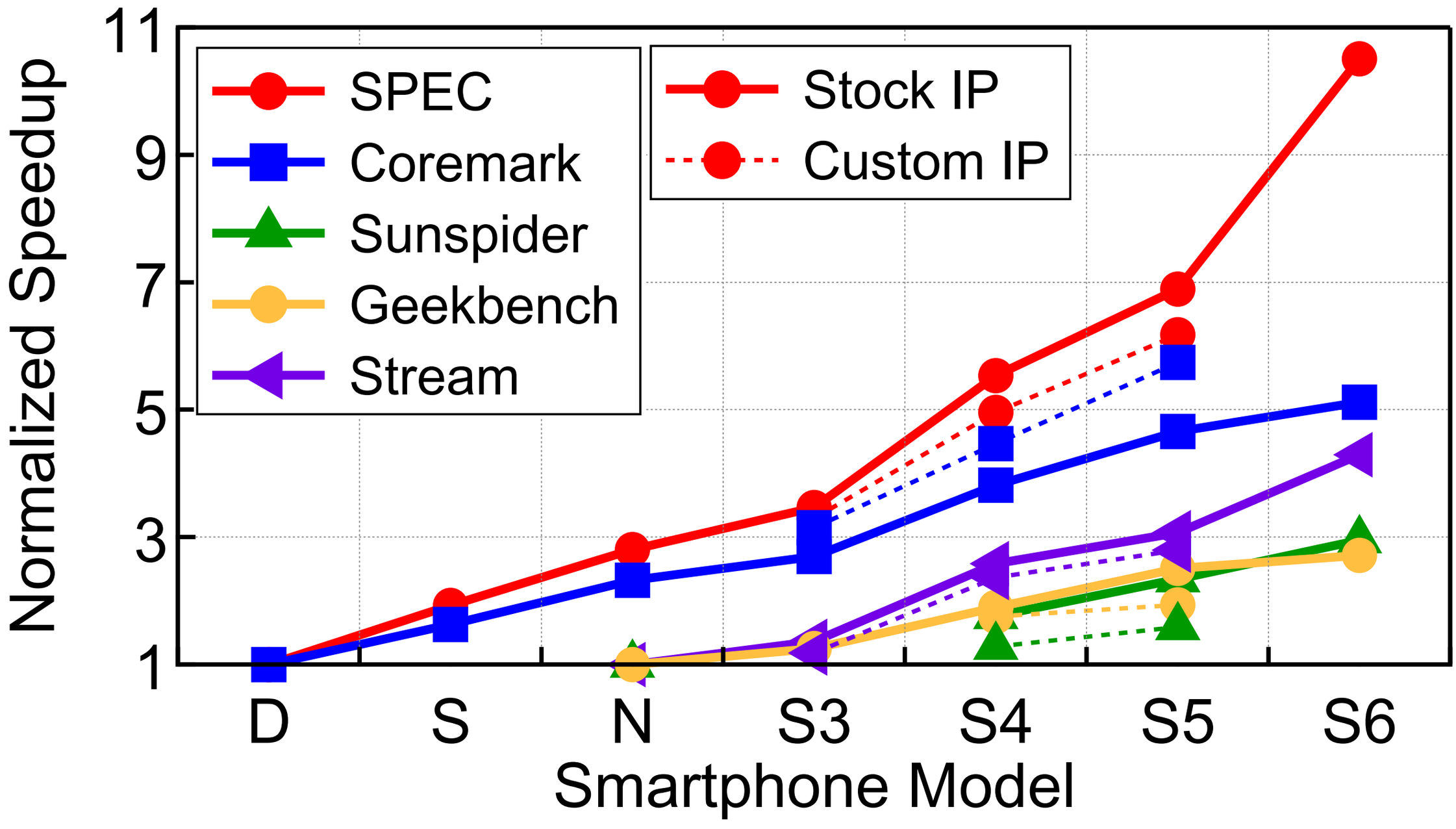
- Scale of trials (> 50 trials / configuration)
- Validation keyword prevents scripters



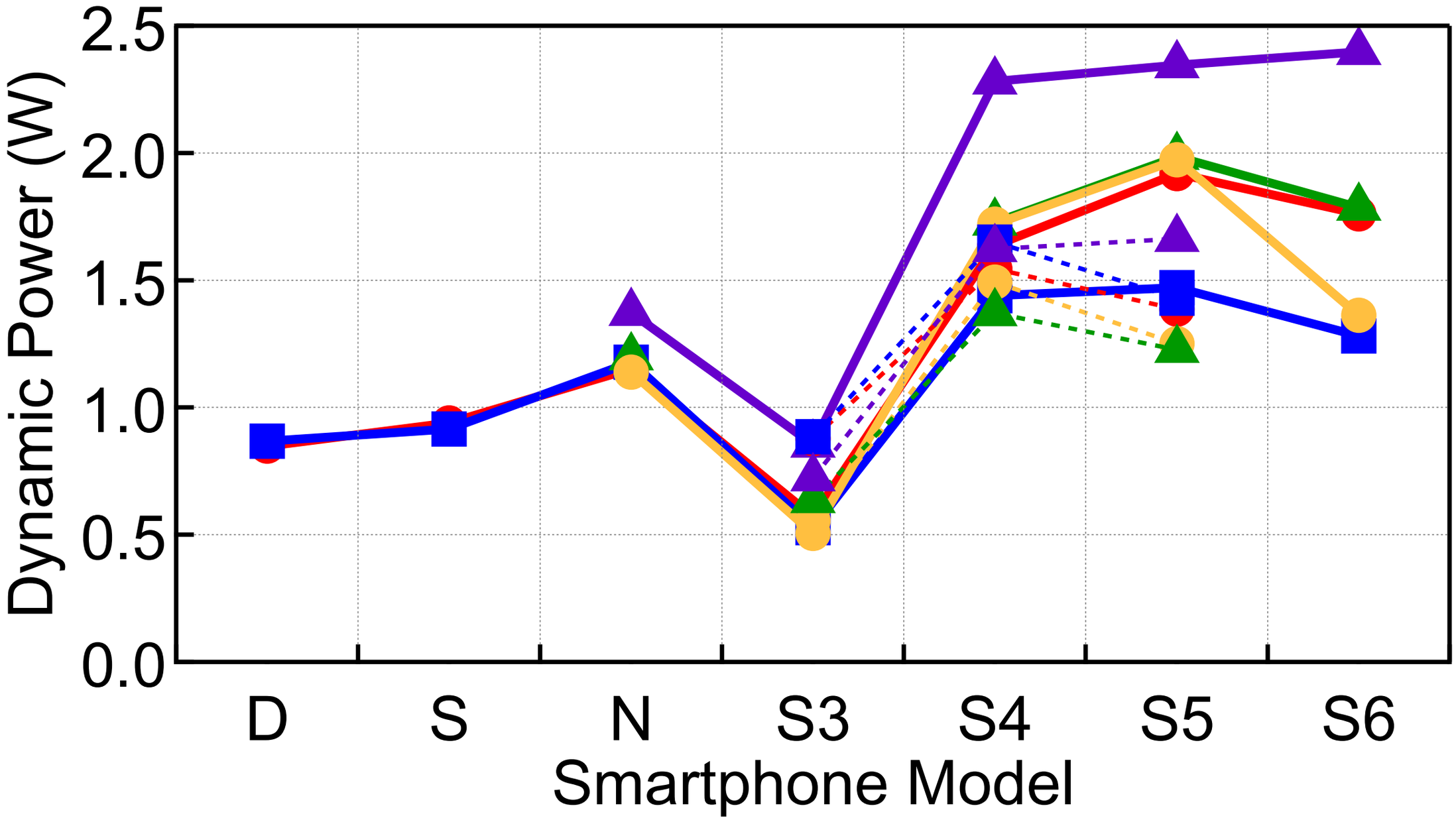
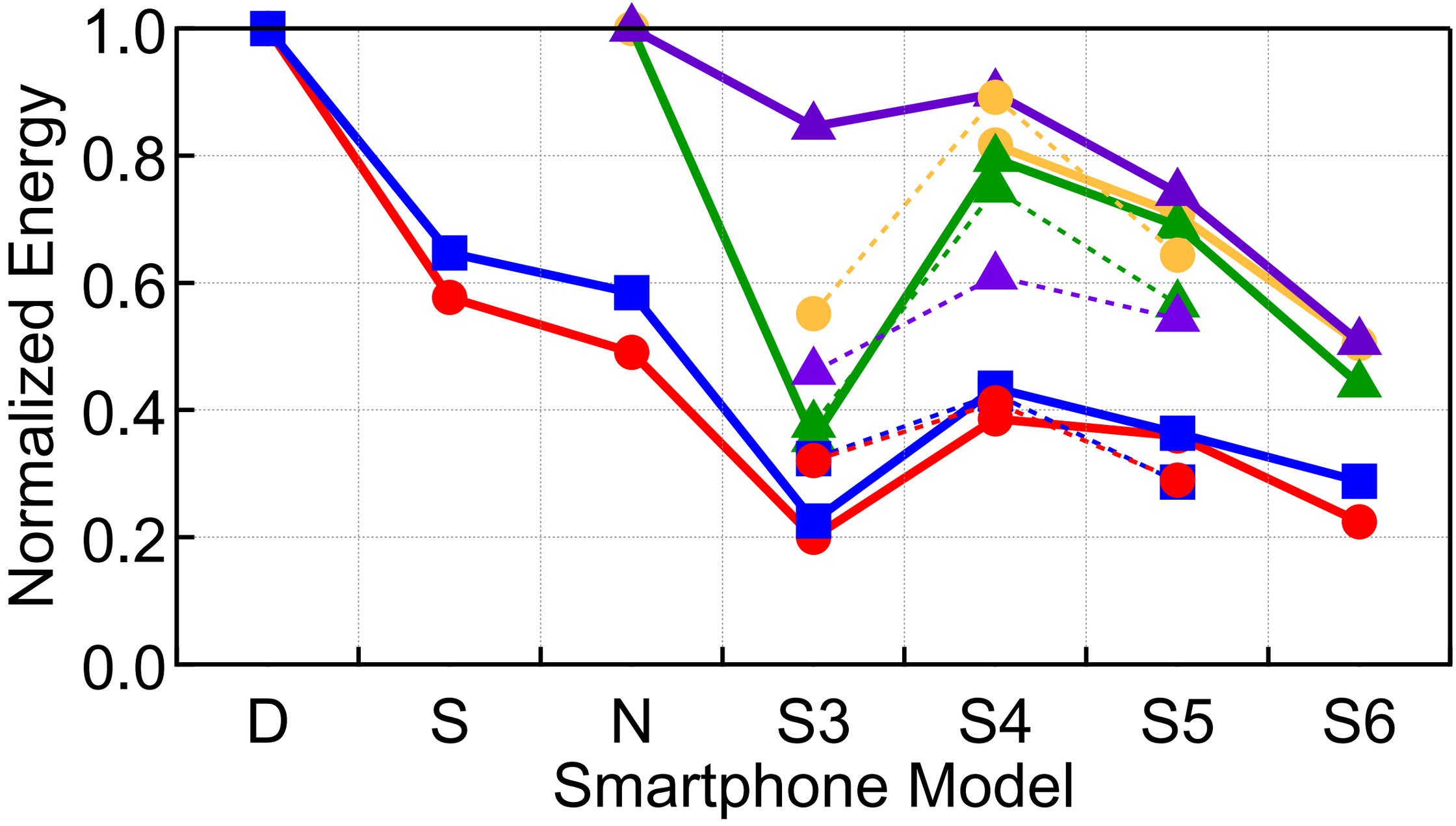
Phone Mapping



Other CPUs and Benchmarks: Perf



Other CPUs and Benchmarks: Power



Other CPUs and Benchmarks: Energy