
Matthew Halpern    Yuhao Zhu    Vijay Janapa Reddi
Dept. of Electrical and Computer Engineering
The University of Texas at Austin
Snake
2000
Mobile Device
Mobile Device

Touchscreen
Mobile Device

Touchscreen  Cellular  WiFi  Bluetooth
Mobile Device

- Touchscreen
- Cellular
- WiFi
- Bluetooth
- Camera
- GPS
- Sensors
- Battery
Mobile Device

- Touchscreen
- Cellular
- WiFi
- Bluetooth
- Camera
- GPS
- Sensors
- Battery

System-On-A-Chip
System-On-A-Chip
System-On-A-Chip
System-On-A-Chip

CPU
System-On-A-Chip

CPU

GPU
System-On-A-Chip

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

- GPU
- CPU
- Network-On-Chip
- Accelerators
Normalized ARM Marketshare (%)

Year


ARM11 A8 A5 A9 A15 A7 A53 A57
Mobile CPU design is fast-paced.
Conventional Research Scope
Conventional Research Scope

- Software
- Hardware
Conventional Research Scope

Bottlenecks

Software

Hardware
Conventional Research Scope

Software  ✦  Hardware

Bottlenecks

Performance
Conventional Research Scope

Bottlenecks

Software

Hardware

Performance
Conventional Research Scope

Bottlenecks

Software

Hardware

Performance
Expanding the Research Scope

- Hardware
- Software
- Performance
- Bottlenecks
Expanding the Research Scope

Bottlenecks

Applications

Processor

Performance
Expanding the Research Scope

Conventional Research Scope

Bottlenecks

Applications ➔ Processor

Performance
Expanding the Research Scope

Conventional Research Scope

End-Users

Applications

Processor

Bottlenecks

Performance
Expanding the Research Scope

Conventional Research Scope

End-Users \rightarrow Features \rightarrow Applications \rightarrow Performance \rightarrow Processor

Bottlenecks

Expanding the Research Scope

End-Users \rightarrow Features \rightarrow Applications \rightarrow Performance \rightarrow Processor

Bottlenecks
Expanding the Research Scope

Conventional Research Scope

- Bottlenecks

End-Users → Applications → Processor

Features → Performance

Satisfaction
Expanding the Research Scope

Conventional Research Scope

End-Users - Applications - Processor

Features - Performance

Bottlenecks

Satisfaction

Mobile Device
Expanding the Research Scope

Conventional Research Scope

End-Users

Features

Applications

Performance

Processor

Power Budgets

Mobile Device

Satisfaction

Bottlenecks
Expanding the Research Scope

- End-Users
- Applications
- Processor
- Mobile Device

Conventional Research Scope

Bottlenecks

Features

Performance

Power Consumption

Satisfaction

Power Budgets
Expanding the Research Scope

Our Scope

End-Users → Features → Applications → Performance → Processor → Power Budgets → Mobile Device

Bottlenecks

Satisfaction

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

1. Has mobile CPU efficiency improved?
Characterize how the interactions between mobile CPU, end-user, and mobile device have changed over time through real-world measurement

1. Has mobile CPU efficiency improved?
2. Have mobile CPU advancements improved end-user satisfaction?
Characterize how the interactions between mobile CPU, end-user, and mobile device have changed over time through real-world measurement

1. Has mobile CPU efficiency improved?
2. Have mobile CPU advancements improved end-user satisfaction?
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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[Images of smartphones for each year from 2009 to 2015]
Capturing Real-world Mobile CPU Trends from Off-the-Shelf Smartphones

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<td>Cores</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
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<td>4 (+4)</td>
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<td>1 GB</td>
<td>2 GB</td>
<td>2 GB</td>
<td>3 GB</td>
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Has mobile CPU efficiency improved?
Has mobile CPU **efficiency** improved?

- Performance
- Energy
Substantial Performance Improvements
Substantial Performance Improvements
Substantial Performance Improvements

Year

Speedup

Coremark

SPEC
Substantial Performance Improvements

Speedup

Year

Coremark

SPEC
Substantial Performance Improvements

What are the key architectural contributors?
Speedup = IPC Speedup \times \text{Clock Speedup}
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup

- A8
- 32-bit
- Dual-Issue


Speedup

Frequency

IPC

Legend:
- Yellow triangle: Frequency
- Green diamond: IPC
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup \times \text{Clock Speedup}
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup
Speedup = IPC Speedup x Clock Speedup

A8 ➔ A9 ➔ A15 ➔ A57

32-bit ➔ 64-bit

Dual-Issue ➔ Triple-Issue

In-Order ➔ Out-of-Order ➔ Aggressive Out-of-Order

Aggressive Mem Hierarchy

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<tr>
<td>2015</td>
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Aggressive core scaling techniques have provided mobile CPUs substantial performance improvements.
Excessive Power Consumption

In-Order → A8 ← A9 → A15 ← A57 →

In-Order → Out-of-Order ← Aggressive Out-of-Order
Excessive Power Consumption

- A8
- A9
- A15
- A57
- In-Order
- Out-of-Order
- Aggressive Out-of-Order

Power (mW)

- Coremark
- SPEC

Year

Excessive Power Consumption

- A8
- A9
- A15
- A57
- In-Order
- Out-of-Order
- Aggressive Out-of-Order

<table>
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<th>Year</th>
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<tr>
<td>2009</td>
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<tr>
<td>2010</td>
<td>950</td>
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<td>2012</td>
<td>1050</td>
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<td>2013</td>
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<td>2014</td>
<td>1350</td>
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<td>2015</td>
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</table>
Excessive Power Consumption

- A8
- A9
- A15
- A57
- In-Order
- Out-of-Order
- Aggressive Out-of-Order

Power (mW)

Year

- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015

Coremark

SPEC

Excessive Power Consumption

0


Power (mW)

1500

1000

500

0
Excessive Power Consumption

- A8
- A9
- A15
- A57
- In-Order
- Out-of-Order
- Aggressive Out-of-Order
- 65 nm

Power (mW)

- Coremark
- SPEC

Year

- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015
Excessive Power Consumption

- A8
- A9
- A15
- A57
- In-Order
- Out-of-Order
- Aggressive Out-of-Order
- 65 nm
- 45 nm

Power (mW)

Year

Coremark
SPEC
Excessive Power Consumption

- A8
- A9
- A15
- A57
- In-Order
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- Aggressive Out-of-Order
- 65 nm
- 45 nm

Power (mW)

- Coremark
- SPEC

Year

- 2009
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- 2013
- 2014
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Excessive Power Consumption

- A8
- A9
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- 65 nm
- 45 nm
- 32 nm

Power (mW)

Year

- 2009
- 2010
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- 2013
- 2014
- 2015

Coremark

SPEC
Excessive Power Consumption

- A8
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- 65 nm
- 45 nm
- 32 nm
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015
- Coremark
- SPEC
- HKMG

Power (mW)
Excessive Power Consumption

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- A8
- A9
- A15
- A57
- In-Order
- Out-of-Order
- Aggressive Out-of-Order
- 65 nm
- 45 nm
- 32 nm
- 28 nm

Coremark
SPEC

HKMG
Excessive Power Consumption

Power (mW)

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HKMG
Excessive Power Consumption

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- 28 nm
- 14 nm
- HKMG

Memory Activity

- Coremark
- SPEC

Year

- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015

Power (mW)
Excessive Power Consumption

Power (mW)

Year

Coremark

SPEC

HKMG

Single-core Thermal Design Point

Memory Activity

Excessive Power Consumption
Mobile CPUs designs are beginning to approach a **power wall**.
Mobile CPU performance improvements are in an era of energy efficiency stagnation.
Incorporating the End-User

Diagram:
- End-Users
- Applications
- Processor
- Mobile Device

Connections:
- Features
- Satisfaction
- Performance
- Power Consumption
- Power Budgets

Concepts:
- Bottlenecks
Incorporating the End-User

- End-Users
- Applications
- Processor
- Mobile Device

Features → Performance → Power Budgets

Satisfaction → Power Consumption
Incorporating the End-User

Diagram showing the relationships between End-Users, Applications, Processor, Mobile Device, Features, Satisfaction, Performance, Power Consumption, and Power Budgets. The diagram indicates bottlenecks in the system.
Incorporating the End-User

End Users

Applications

Processor

Mobile Device

Features

Satisfaction

Bottlenecks

Performance

Power Budgets

Power Consumption
Incorporating the End-User

End-Users -> Features -> Applications -> Performance -> Processor -> Power Budgets -> Mobile Device

Satisfaction -> Bottlenecks -> Power Consumption
Have mobile CPU advancements improved end-user satisfaction?
Have mobile CPU advancements improved end-user satisfaction?

1. Is single-core performance necessary?
Have mobile CPU advancements improved end-user satisfaction?

1. Is single-core performance necessary?
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**
Leveraging the **Crowd** to Achieve **Scale**

Over **25,000** participants!
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
Survey Design

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Emulating the Mobile CPU Evolution

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Emulating the Mobile CPU Evolution

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Year
Emulating the Mobile CPU Evolution

<table>
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Emulating the Mobile CPU Evolution

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## Emulating the Mobile CPU Evolution

<table>
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*Note: 'N' indicates year with no additional information.*
Emulating the Mobile CPU Evolution

<table>
<thead>
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<th>Year</th>
<th>Cores</th>
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<tr>
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Emulating the Mobile CPU Evolution

<table>
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<td>2012</td>
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</tr>
<tr>
<td>2014</td>
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</tr>
</tbody>
</table>
Emulating the Mobile CPU Evolution

Cores

4
3
2
1

D S

2009 2010 2011 2012 2013 2014

Year

S3 S4 S5

N
# Emulating the Mobile CPU Evolution

The table below illustrates the evolution of mobile CPUs from 2009 to 2014, focusing on the number of cores and specific models (S3, S4, S5). Each year is marked with the number of cores available (1, 2, 3, 4) and the corresponding model number:

- **2009**: 1 core with S3 model, 2 cores with S5 model
- **2010**: 2 cores with S5 model
- **2011**: 3 cores with S5 model
- **2012**: 4 cores with S5 model
- **2013**: 4 cores with S5 model
- **2014**: 4 cores with S5 model

<table>
<thead>
<tr>
<th>Year</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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</table>
## Emulating the Mobile CPU Evolution

<table>
<thead>
<tr>
<th>Cores</th>
<th>4</th>
<th>3</th>
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<th>1</th>
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<th>S4</th>
<th>S5</th>
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<td></td>
<td>D</td>
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<tr>
<td></td>
<td>422</td>
<td>729</td>
<td>1036</td>
<td>1497</td>
<td>1958</td>
<td>2457</td>
<td></td>
</tr>
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</table>

**S5 Clock Frequency**
Emulating the Mobile CPU Evolution

<table>
<thead>
<tr>
<th>S5 Cores Enabled</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
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<tbody>
<tr>
<td>4</td>
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<td></td>
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</tr>
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<td></td>
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<td>N</td>
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<tr>
<td>1</td>
<td>D</td>
<td>S</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>S5 Clock Frequency</th>
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</thead>
<tbody>
<tr>
<td>422</td>
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<tr>
<td>729</td>
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<tr>
<td>1036</td>
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<tr>
<td>1497</td>
</tr>
<tr>
<td>1958</td>
</tr>
<tr>
<td>2457</td>
</tr>
</tbody>
</table>
Putting the Pieces Together

Record User  Parametrized Replay  Post Survey  Crowdsourcing
Putting the Pieces Together

Record User  Parametrized Replay  Post Survey  Crowdsourse
Putting the Pieces Together

- Record User
- Parametrized Replay
- Post Survey
- Crowdsourcing
Putting the Pieces Together

Record User  Parametrized Replay  Post Survey  Crowdsourced

CPU Frequency  CPU Cores  GPU Frequency
Putting the Pieces Together

Record User  Parametrized Replay  Post Survey  Crowdsourcing
Putting the Pieces Together

Record User  Parametrized Replay  Post Survey  Crowdsource

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
Putting the Pieces Together

Record User  Parametrized Replay  Post Survey  Crowdsourc
Putting the Pieces Together

Record User  Parametrized Replay  Post Survey  Crowdsource
Putting the Pieces Together

Record User  Parametrized Replay  Post Survey  Crowdsourcer
Putting the Pieces Together

Record User

Parametrized Replay

Post Survey

Crowdsourcing
Do we need single-core performance?
Do we need **single-core** performance?

![Graph](image)

**Legend:**
- 1.0: Very Dissatisfied
- 2.0: Dissatisfied
- 3.0: Neutral
- 4.0: Satisfied
- 5.0: Very Satisfied
Do we need single-core performance?
Do we need single-core performance?
Do we need single-core performance?
Do we need **single-core** performance?
Do we need single-core performance?
Do we need single-core performance?
Do we need single-core performance?
Do we need single-core performance?

<table>
<thead>
<tr>
<th>Cores Enabled</th>
<th>422.4 MHz</th>
<th>729.6 MHz</th>
<th>1036.8 MHz</th>
<th>1497.6 MHz</th>
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<tbody>
<tr>
<td>1</td>
<td>2.70</td>
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<td>2.67</td>
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<td>2.66</td>
<td>2.79</td>
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<td>4.06</td>
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<td>2.85</td>
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<td>3.72</td>
<td>3.90</td>
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<td>2.56</td>
<td>4.08</td>
<td>3.89</td>
<td>3.82</td>
<td>4.14</td>
</tr>
</tbody>
</table>

- 1.0: Very Dissatisfied
- 2.0: Dissatisfied
- 3.0: Neutral
- 4.0: Satisfied
- 5.0: Very Satisfied
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?
Do we need multi-core performance?
Do we need multi-core performance?
Do we need **multi-core** performance?
Do we need **multi-core** performance?
Do we need multi-core performance?
Do we need multi-core performance?
Do we need **multi-core performance**?
Do we need **multi-core** performance?
Do we need multi-core performance?
Do we need multi-core performance?

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?
Does **graphics** performance matter more than CPU performance?
Does graphics performance matter more than CPU performance?
Does graphics performance matter more than CPU performance?
Does **graphics** performance matter more than CPU performance?

![Graph showing comparisons of benchmarks](image-url)
Does graphics performance matter more than CPU performance?

- **Gladiator**: 2.27 MHz
- **Facebook**: 2.88 MHz
- **Chrome CNN**: 3.24 MHz
- **Photoshop**: 3.76 MHz
- **Youtube**: 4.12 MHz
- **Epic Citadel**: 200.0 MHz
- **Angry Birds**: 389.0 MHz
- **GPU Frequency (MHz)**: 462.4 MHz - 578.0 MHz
Does **graphics** performance matter more than CPU performance?

<table>
<thead>
<tr>
<th>Benchmarks</th>
<th>200.0</th>
<th>320.0</th>
<th>389.0</th>
<th>462.4</th>
<th>578.0</th>
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<tr>
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<td>2.27</td>
<td>2.88</td>
<td>3.24</td>
<td>3.76</td>
<td>4.12</td>
</tr>
<tr>
<td>Facebook</td>
<td>4.06</td>
<td>3.89</td>
<td>4.04</td>
<td>3.94</td>
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<tr>
<td>Chrome CNN</td>
<td>4.23</td>
<td>4.31</td>
<td>4.22</td>
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<td>4.00</td>
<td>4.19</td>
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<td>Youtube</td>
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<td>4.38</td>
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<td>4.51</td>
<td>4.48</td>
<td>4.57</td>
<td>4.33</td>
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<td>4.23</td>
<td>4.57</td>
<td>4.44</td>
<td>4.30</td>
<td>4.60</td>
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**GPU Frequency (MHz)**
Does **graphics** performance matter more than CPU performance?

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<td>Photoshop</td>
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<td>4.38</td>
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<td>Epic Citadel</td>
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<td>4.57</td>
<td>4.44</td>
<td>4.30</td>
<td>4.60</td>
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</tbody>
</table>

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**.
At the Mercy of Power Constraints
At the Mercy of Power Constraints
At the Mercy of Power Constraints
At the Mercy of Power Constraints

Diagram:
- End-Users
- Applications
- Processor
- Mobile Device

Arrows indicate:
- Features
- Performance
- Power Budgets
- Power Consumption

Keywords:
- Hardware
- Software
- Mobile Device
- Processor
- Applications
- End-Users
- Satisfaction
- Performance
- Power Consumption
- Bottlenecks
- At the Mercy of Power Constraints

Diagram illustration:
- End-Users → Features → Applications → Performance → Processor → Power Budgets → Mobile Device
- Power Consumption

Text:
- "At the Mercy of Power Constraints"
At the Mercy of Power Constraints
At the Mercy of Power Constraints

End-Users → Features → Applications → Performance → Bottlenecks → Processor → Power Budgets → Mobile Device

Satisfaction

Power Consumption
How has the rest of the mobile device evolved around the CPU?
Sharing the Power Budget: Device-level
Sharing the Power Budget: Device-level

<table>
<thead>
<tr>
<th>Year</th>
<th>Power (watts)</th>
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<tbody>
<tr>
<td>2009</td>
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</tr>
<tr>
<td>2010</td>
<td></td>
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<tr>
<td>2011</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>2014</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
</tr>
</tbody>
</table>

- Display
- Radio
- CPU: Single-core
- CPU: Multi-core
Sharing the Power Budget: Device-level

![Bar chart showing power consumption over years for different components.]

- Display
- Radio
- CPU: Single-core
- CPU: Multi-core

Year


Power (watts)
Sharing the Power Budget: Device-level

- Display
- CPU: Single-core
- CPU: Multi-core

Power (watts)

Year

- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015
Sharing the Power Budget: Device-level

Year

Power (watts)
0, 2, 4, 6, 8

Display
CPU: Single-core
Radio
CPU: Multi-core
Sharing the Power Budget: Device-level

Power (watts)

- Display
- Radio
- CPU: Single-core
- CPU: Multi-core

Year
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015

Power (watts)
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015

Year

Sharing the Power Budget: Device-level

Thermal Throttling

- Display
- Radio
- CPU: Single-core
- CPU: Multi-core

Power (watts)

Year

Mobile SoC: Unsustainable By Design
Mobile SoC: Unsustainable By Design

Reported TDP (watts)

Phone

Galaxy S5

Galaxy S6

CPU: A15

CPU: A7

GPU

Other
Mobile SoC: Unsustainable By Design

<table>
<thead>
<tr>
<th>Phone</th>
<th>Reported TDP (watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxy S5</td>
<td>6</td>
</tr>
<tr>
<td>Galaxy S6</td>
<td>4</td>
</tr>
</tbody>
</table>

Legend:
- **CPU: A15**
- **CPU: A7**
- **GPU**
- **Other**
Mobile SoC: Unsustainable By Design

Reported TDP (watts)

- CPU: A15
- CPU: A7
- GPU
- Other

Phone

Galaxy S5

Galaxy S6
Mobile SoC: Unsustainable By Design

![Bar chart showing the reported TDP (watts) for Galaxy S5 and Galaxy S6.]

- **Galaxy S5**:
  - CPU: A15
  - CPU: A7
  - GPU
  - Other

- **Galaxy S6**:
  - CPU: A15
  - CPU: A7
  - GPU
  - Other
Mobile SoC: Unsustainable By Design

Reported TDP (watts)

**Galaxy S5**
- CPU: A15: 6 watts
- CPU: A7: 1 watt
- GPU: 3 watts
- Other: 1 watt

**Galaxy S6**
- CPU: A15: 6 watts
- CPU: A7: 1 watt
- GPU: 3 watts
- Other: 1 watt

---

**Reported TDP (watts)**

0  1  2  3  4  5  6  7  8  9  10  11  12

**Phone**

**Galaxy S5**

**Galaxy S6**

**CPU: A15**

**CPU: A7**

**GPU**

**Other**
Mobile SoC: Unsustainable By Design

<table>
<thead>
<tr>
<th>Phone</th>
<th>CPU: A15</th>
<th>CPU: A7</th>
<th>GPU</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxy S5</td>
<td>3.5 W</td>
<td>0.5 W</td>
<td>5 W</td>
<td>0.5 W</td>
</tr>
<tr>
<td>Galaxy S6</td>
<td>3.5 W</td>
<td>0.5 W</td>
<td>5 W</td>
<td>0.5 W</td>
</tr>
</tbody>
</table>

3.5 W TDP Budget
Tying It All Together

- **End-Users**
  - Features
  - Satisfaction

- **Applications**
  - Performance

- **Processor**
  - Capabilities
  - Power Budgets

- **Mobile Device**
  - Power Consumption
A Call to Action

- End-Users
- Applications
- Processor
- Mobile Device
A Call to Action

Use metrics that incorporate end-user

- End-Users
- Applications
- Processor
- Mobile Device
A Call to Action

Use metrics that incorporate end-user

Identify user-critical application segments
A Call to Action

Use metrics that incorporate end-user

End-Users

Identify user-critical application segments

Applications

Understand application characteristics

Processor

Mobile Device
A Call to Action

- Use metrics that incorporate end-user
- Identify user-critical application segments
- Understand application characteristics
- Deviate from desktop scaling and embrace the era specialization
A Call to Action

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

<table>
<thead>
<tr>
<th>Core</th>
<th>SSSL</th>
<th>S3S</th>
<th>S4S</th>
<th>S5Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N</td>
<td>D</td>
<td>S</td>
<td></td>
</tr>
</tbody>
</table>

#### Frequency (MHz)

**Cores Enabled**

- **4 Cores**: 422.4, 729.6, 1038.6, 1497.6, 1958.4, 2457.6
- **3 Cores**: 422.4, 729.6, 1038.6, 1497.6, 1958.4, 2457.6
- **2 Cores**: 422.4, 729.6, 1038.6, 1497.6, 1958.4, 2457.6
- **1 Core**: 422.4, 729.6, 1038.6, 1497.6, 1958.4, 2457.6

#### Examples

- **(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

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

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

# Apple CPUs

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

[Link to source](http://www.anandtech.com/show/9686/the-apple-iphone-6s-and-iphone-6s-plus-review/4)
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 fluidity)?

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

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

Task 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
   - 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.
Crowdsourcing Considerations

Task Design

▷ Open-ended question

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
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   - 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.
Crowdsourcing Considerations

**Task Design**

- Open-ended question
- Well-defined answers
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

▷ Open-ended question
▷ Well-defined answers

Worker Recruitment and Incentive

▷ $0.10 / task
▷ $8.00 / hour wage

Data Integrity
Crowdsourcing Considerations

Task Design

▷ Open-ended question
▷ Well-defined answers

Worker Recruitment and Incentive

▷ $0.10 / task
▷ $8.00 / hour wage

Data Integrity

▷ Scale of trials (> 50 trials / configuration)
Crowdsourcing Considerations

**Task Design**
- Open-ended question
- Well-defined answers

**Worker Recruitment and Incentive**
- $0.10 / task
- $8.00 / hour wage

**Data Integrity**
- Scale of trials (> 50 trials / configuration)
- Validation keyword prevents scripters
Phone Mapping

The figure shows a box plot for mapping error (%) across different phones (D, S, N, S3S, S4S). The mapping error is plotted on the y-axis, and the phones are listed on the x-axis. The box plots indicate the distribution of mapping errors, with the central line representing the median, the box boundaries showing the interquartile range, and the whiskers indicating the range of the data excluding outliers. Outliers are marked with plus signs (+).
Other CPUs and Benchmarks: Power

![Graph showing dynamic power consumption across different smartphone models](image-url)
Other CPUs and Benchmarks: Energy

Normalized Energy vs Smartphone Model

- D
- S
- N
- S3
- S4
- S5
- S6