Rethink energy accounting with cooperative game theory

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Energy accounting by software

• How much energy does a software principal consume given a time period?
  – Software evaluation
  – Energy management in operating system
Why is it so hard?

Too many (hardware) resources
Expensive to account all resource usage by a software principal

Ifix.com iPhone 5S teardown

Chipworks.com
The state of the art
Policy V: linear model based

\[ E = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p \]

Predictors \( x_i \): Software-visible resource usage

H. Zeng et al, "ECOSystem: managing energy as a first class operating system resource," ASPLOS’02.
A. Kansal et al, "Virtual machine power metering and provisioning," SoCC’10.
Policy V: linear model based

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Predictors \( x_i \): Software-visible resource usage

\( n \) principals contribute to the predictors

\[
\begin{align*}
x_1 &= x_{1,1} + \ldots + x_{1,n} \\
\vdots & \quad \vdots \\
x_p &= x_{p,1} + \ldots + x_{p,n}
\end{align*}
\]

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\[ \vdots \]
\[ x_p = x_{p,1} + \ldots + x_{p,n} \]

Energy contribution by principal \( i \)

\[ \phi_i = \beta_1 x_{1,i} + \ldots + \beta_p x_{p,i} \]

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Problem 1

\[ E = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p \]

**Predictors must be software visible**

CPU cycles, amount of data sent, memory usage……..

Practically infeasible to account for all resource usage
Problem 2

\[ E = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p \]

**Model must be linear**

McCullough et al (NSDI’11) & our own MobiSys’11

Linear can be problematic
Problem 3

\[ E = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p \]

**Constant factor** (\( \beta_0 \)) **is difficult to attribute**

Problem 1 makes Problem 3 bigger
These problems are fundamental
Plus, we don’t really have a ground truth!
Two computer engineers struggled for two years
Energy Consumption is A Cooperative Game
Cooperative Game Theory

How much of the surplus shall each player receive?
The Shapley value [Shapley 1953]

Received Nobel Prize in Economics 2012
More information necessary!
More information necessary!
What player \( i \) shall receive

\[
\phi_i(E(N)) = \sum_{S \subseteq N \setminus \{i\}} \frac{E(S \cup \{i\}) - E(S)}{(|N| - |S|)(|N|)}
\]

\( N = \{1, 2, \ldots, n\} \) \quad \text{Set of players (grand coalition)}

\( S \) \quad \text{Subset of } N \text{ (coalition)}

\( E(S) \) \quad \text{Surplus of the game when } S \text{ are playing}
Shapley value explained

\[ \phi_i(E(N)) = \sum_{S \subseteq N \setminus \{i\}} \frac{E(S \cup \{i\}) - E(S)}{(|N| - |S|)(|N|)} \]
Shapley value explained

\[ \phi_i(E(N)) = \sum_{S \subseteq N \setminus \{i\}} \frac{E(S \cup \{i\}) - E(S)}{|N| - |S|}(|N| - |S|) \]
This is the only policy meeting the following four axioms

- **Efficiency**
If replacing one with the other does not make any difference

- Symmetry
If adding the player does not affect any game surplus

- **Null Player**

\[ = 0 \]
The policy must be consistent in all games

- **Additivity**
Energy consumption is a cooperative game

Alice  Bob  Charlie

How much of the surplus shall each player receive?
Energy consumption is a cooperative game

How much energy consumption does a software principal contribute?
Four axioms revisited

- **Efficiency**
If replacing one with the other does not make any difference

- Symmetry
If adding a software does not affect the energy consumption

- **Null Player**

\[ = 0 \]
The policy must be consistent for all time intervals

• Additivity
Shapley value is the ground truth for energy accounting!

\[ \phi_i(E(N)) = \sum_{S \subseteq N \backslash \{i\}} \frac{E(S \cup \{i\}) - E(S)}{(|N| - |S|)(|N||S|)} \]
It sounds nice but practically…

\[
\phi_i(E(N)) = \sum_{S \subseteq N \setminus \{i\}} \frac{E(S \cup \{i\}) - E(S)}{(|N| - |S|)(|N|)}
\]
Need $E(S)$ for all subsets of $N$
System challenges to obtain all $E(S)$

System energy consumption when $S$ are concurrently running

- $E(S)$ is **highly random**
  - Depends on execution dynamics
  - Depends on hardware configuration

- $E(S)$ **not available for many** $S$
  - $2^N$ subset $S$ in total
System challenges to obtain all $E(S)$

System energy consumption when $S$ are concurrently running

- $E(S)$ is highly random
  - Solution 1: Measure $E$ for short time interval \textit{in situ}
  - Depends on hardware configuration

- $E(S)$ not available for many $S$
  - Solution 1: Measure $E$ for short time interval \textit{in situ}
Challenge I: Shapley value only cares about IF a player participates in a game but not HOW

$\sim 5^{10}$ ways 5 principals can appear in $T$
Challenge I: Shapley value only cares about IF a player participates in a game but not HOW

Only two principals can appear in $T$

Two ways any two principals can appear in $T$

$HW 2$

$HW 1$

$T$
Challenge II: Not all combinations of tasks have been observed

For 5 principals, there are \(2^5 = 32\) different \(S\) for \(E(S)\).
Challenge II: Not all combinations of tasks have been observed

For 2 principals, there are $2^2 = 4$ different $S$ for $E(S)$
10 ms *in situ* measurement by state-of-the-art battery fuel gauge (~95%)

hardware modification incurs negligible power overhead and $
System challenges to obtain all $E(S)$

System energy consumption when $S$ are concurrently running

- $E(S)$ is highly random
  - Solution 1: Measure $E$ for short time interval *in situ*
  - Depends on hardware configuration

- $E(S)$ not available for many $S$
  - Solution 1: Measure $E$ for short time interval *in situ*
System challenges to obtain all $E(S)$

System energy consumption when $S$ are concurrently running

- $E(S)$ is highly random
  - Solution 1: Measure $E$ for short time interval *in situ*
  - Solution 2: Extend $E(S)$ to $E(S, \sigma)$

- $E(S)$ not available for many $S$
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System challenges to obtain all $E(S)$

System energy consumption when $S$ are concurrently running

• $E(S)$ is highly random
  - Solution 1: Measure $E$ for short time interval \textit{in situ}
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• $E(S)$ not available for many $S$
  - Solution 1: Measure $E$ for short time interval \textit{in situ}
  - Solution 3: Estimate missing $E(S, \sigma)$ by observed ones
Information needed by Shapley value
Some $E(S)$ may be missing
Approximate the missing $E(S)$
Approximate the missing $E(S)$
Problem reduced to solving a n-variable linear system

\[
\phi_i(E(N)) = \sum_{S \subseteq N \setminus \{i\}} \frac{E(S \cup \{i\}) - E(S)}{(|N| - |S|)(|S|)}
\]

\[
\sum_{j=1}^{n} \alpha_{i,j} \phi_i(E(N)) + \beta_i = 0, \text{ for } i = 1, \ldots, n
\]
Approximate the “game”

• Some $E(S)$ are approximated

• The Shapley Value of this approximate game is our Shapley value-based accounting or

**Policy Shapley Value (SV)**
Prototype

Texas Instruments PandaBoard
• OMAP 4430 with Android 4.0
How could we evaluate *Policy SV*?

Remember, we don’t really have a ground truth 😞
Three-part indirect evaluation

• How accurate is missing $E(S)$ approximated?
  – Most $E(S)$ observed; ~90% for missing ones

• How good is it in identifying top energy consumer?
  – Disagree with Policy V 19 out 50 cases
  – Experiments show Policy SV is more credible

• How good is it in energy management?
  – Beat Policy V by 10%
How does Policy SV compare against existing policies?
• Benchmark Applications (scripted)
  • Download (HTTP GET)
  • Web (Android built-in browser)
  • Video (ffmpeg)
  • Game (Quake 3)

• Three Scenarios
  • Scenario 1: Web + Download + Android
  • Scenario 2: Video + Download + Android
  • Scenario 3: Game + Download + Android
Policies disagree with each other
Policy V underestimates Game for not considering GPU in the energy model.
Some reflection
Limitations

• Does not work when software activities can not be timed

  – Neither do prior solutions

  – Example: non blocking I/O operations
Limitations (Contd.)

• May not necessarily be accurate for a short period

  – So is the model-based approach

  – Shapley value-based accounting is essentially a statistical average
Limitations (Contd.)

• Does not provide insight into what resources consume the energy
  – The model-based approach does
  – Shapley value-based accounting is blind of resource usage
Advantages over Policy V

- Does not assume linear relations between energy consumption and resource usage
Advantages over Policy V (Contd.)

• Perhaps easier to improve

  – Policy V
    • Improve resource usage accounting
    • Add hardware support for more resources

  – Policy Shapley Value
    • Improve the accuracy of $E(S)$ measurement
Conclusions

• Shapley value is the ground truth for energy accounting

• An approximate can be obtained in practice

• Shapley value-based accounting beats known policies and brings in complementary strength
Interdisciplinary research is awesome!

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