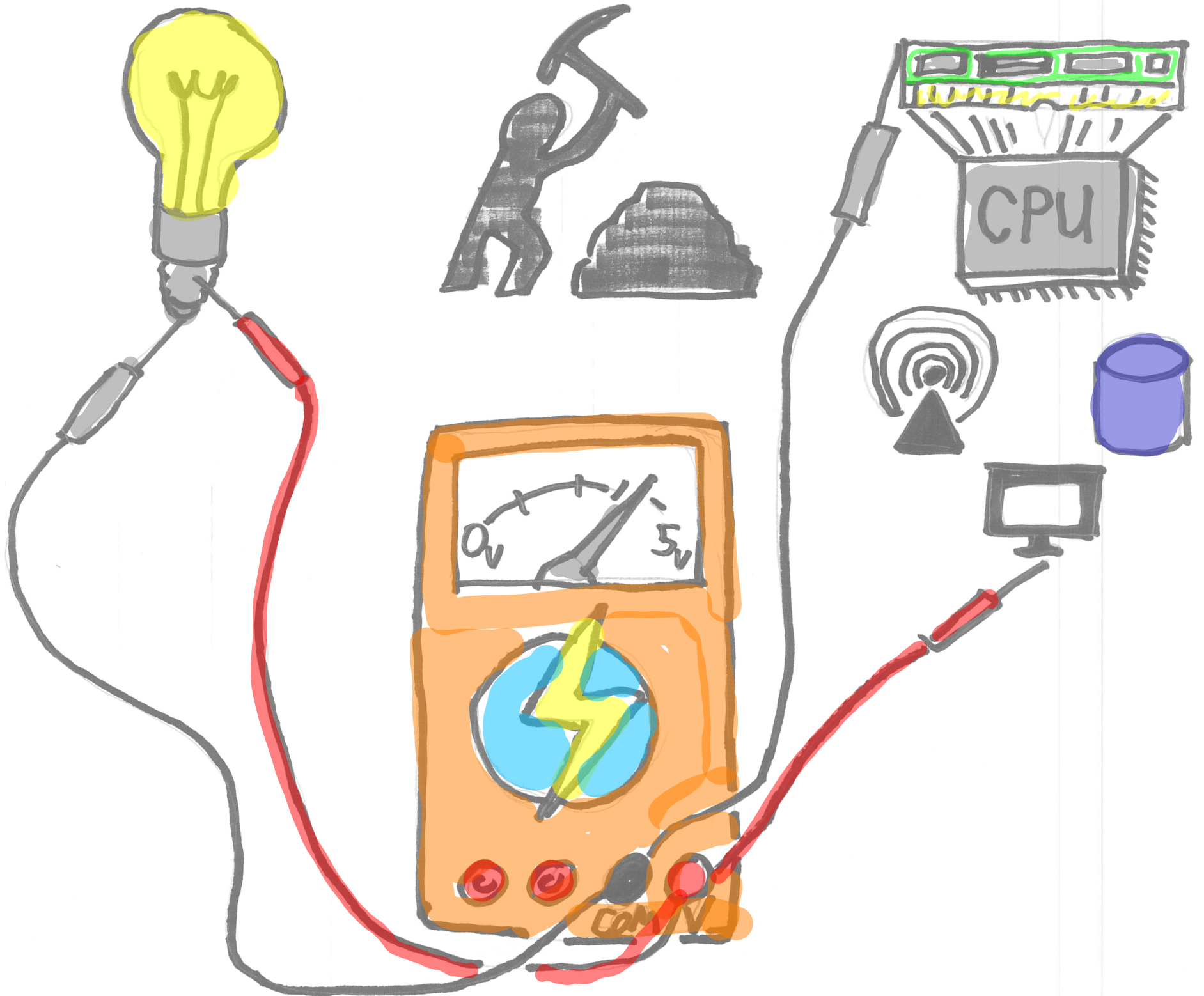


# GREEN

Software Engineering



with  
Abram Hindle  
University of Alberta, CANADA  
hindle1@ualberta.ca





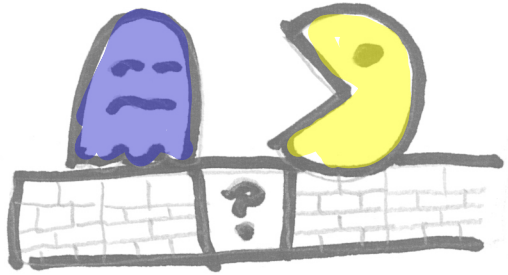
COMPUTING  
HAS A  
COST



# Cost of Work (continuous)



[Chowdhury et al. 2016]

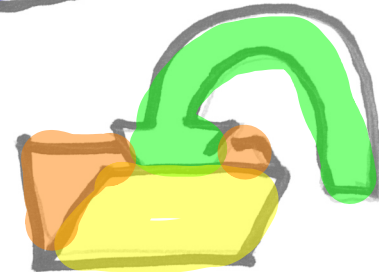


Watts  
W

# Energy Consumed to fulfill a task



SERVICE  
VS  
TASK



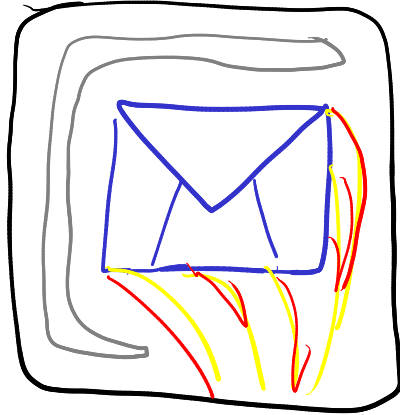
Joules  
J

$$1Ws = 1J$$
$$1Wh = 3600J$$

# Ranking Apps

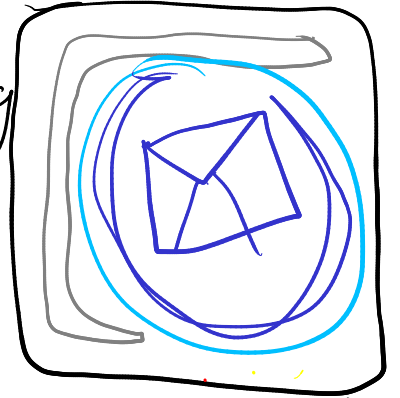
Super Boring  
Email

★ ★ ★ ★ ☆  
4/5



Super Exciting  
Email

★ ★ ★ ☆ ☆  
3/5



Read

5/5 for  
energy efficiency

Read

~~2/5 for  
energy efficiency~~

Send

5/5 for  
energy efficiency

Send

~~2/5 for  
energy efficiency~~

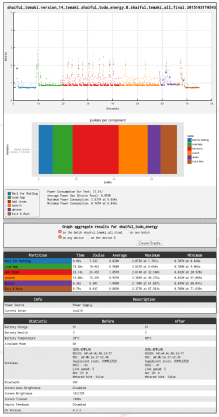
Recv

5/5 for  
energy efficiency

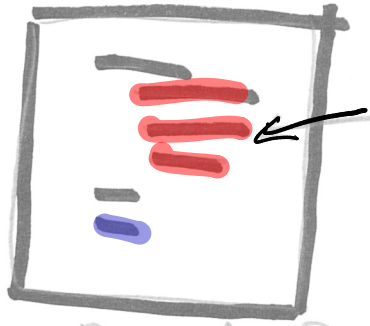
Recv

5/5 for  
energy efficiency

# Measurement



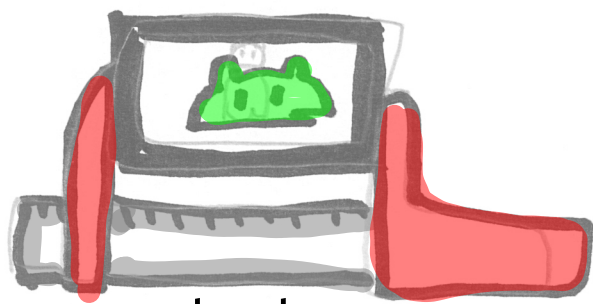
~Mhz Sampling



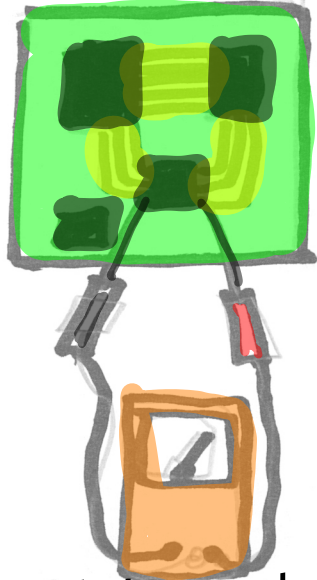
Src Line Resolution

- Droid [Li et al. 2014]

Green Miner  
 [Hindle et al. 2014]  
 [Banerjee et al. 2014]



Whole System Measurement

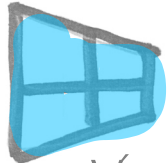


Component Level Measurement

- vbrun300.dll
- grapher.dll

Per Software Component  
 [Gupta et al. 2011]

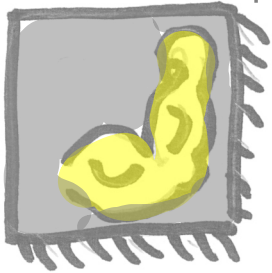
[Gupta et al. 2011]



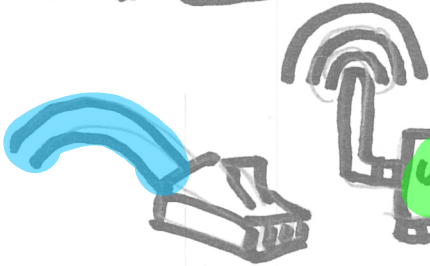
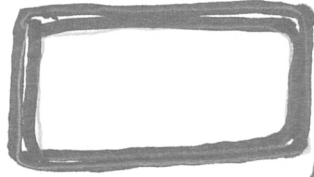
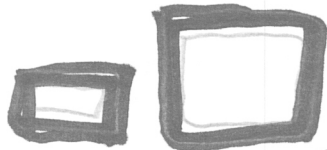
# Models and Generalization

*Models and Generalization*

[Linares-Vasquez et al. 2014]



[Gui et al. 2015]



# Current and Future

*Current and Future*

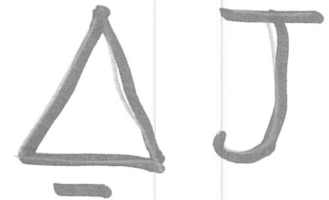


*method*



[Li et al. 2013]

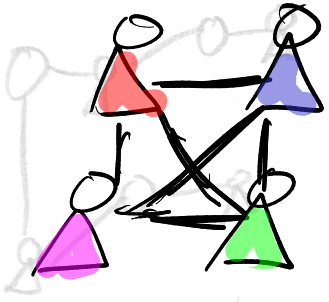
[Hao et al. 2013]



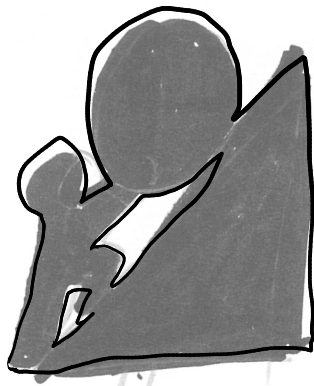
[Sahin et al. 2014]

[Peltonen et al. 2015] [Aggarwal et al. 2015]

[Pathak et al. 2012]



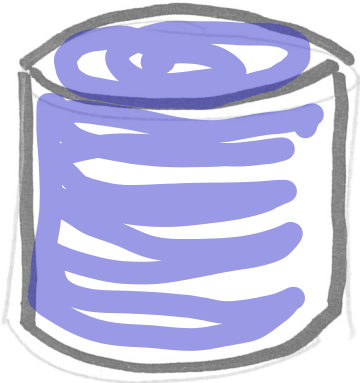
Community



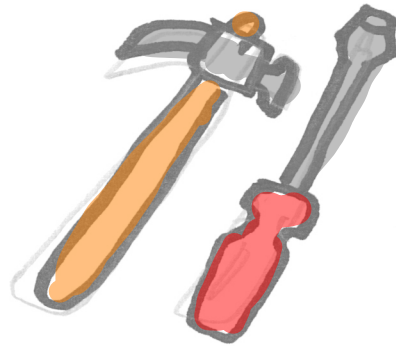
Challenges



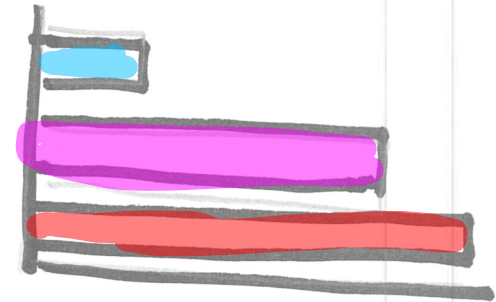
Methodology



Shared Data



Shared Tools



Benchmarks

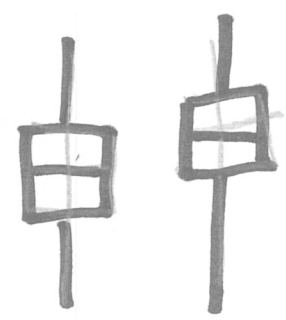
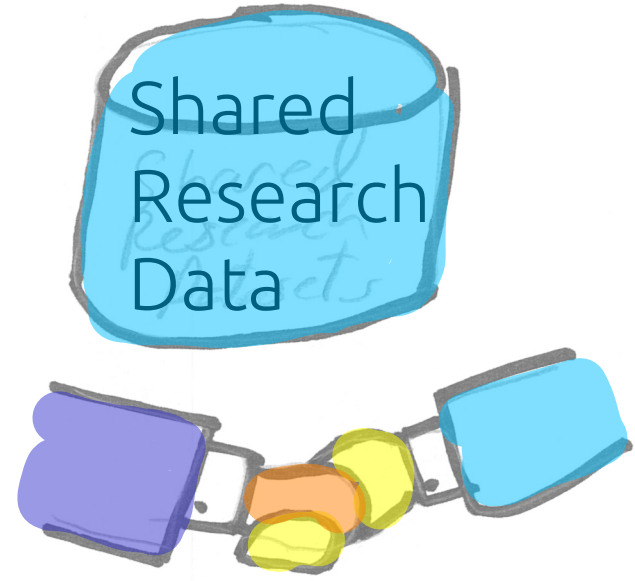
[Jabbarvand et al. 2015]



# Lack Of Data



No Shared  
Energy Data  
and Limited  
Performance  
Data.



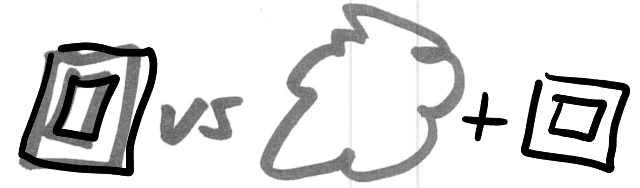
Tests require  
many runs



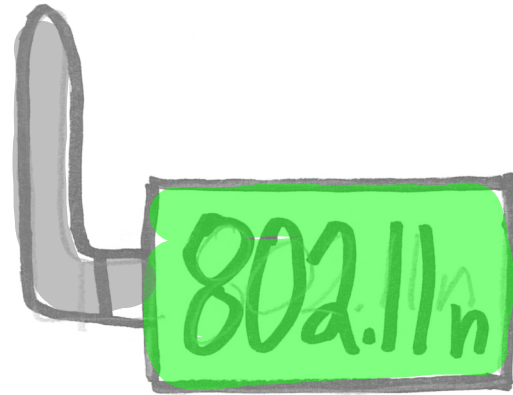
Resources!  
- Lots of Data  
- heterogenous  
data  
- No shared format

# CPU IS NOT ENOUGH

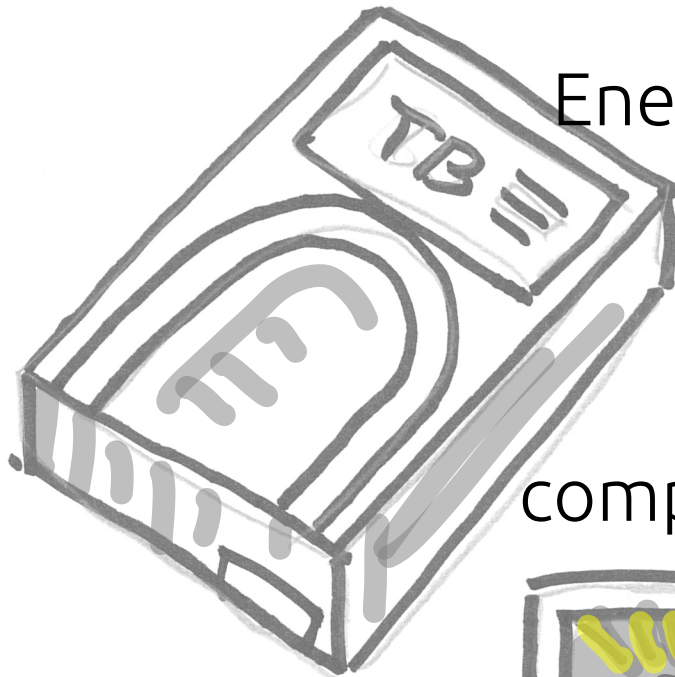
Holistic Measurement



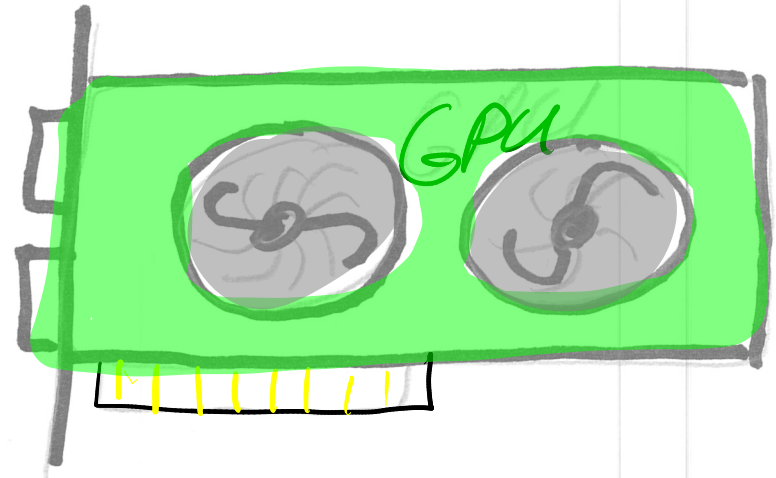
[Moghaddam et al. 2015]



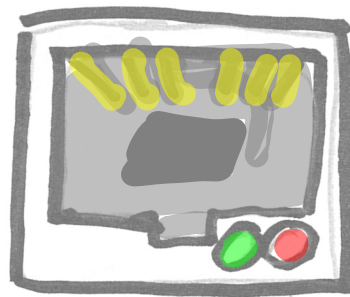
Energy Using Peripherals



I/O  
is  
computation



[Greenawalt et al. 1994]

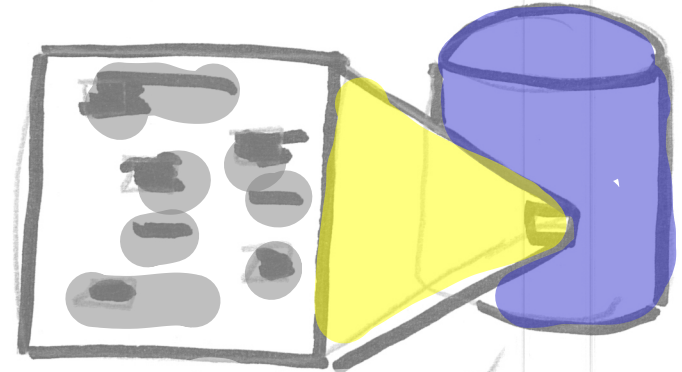


Network

# Non Determinism in SW/HW



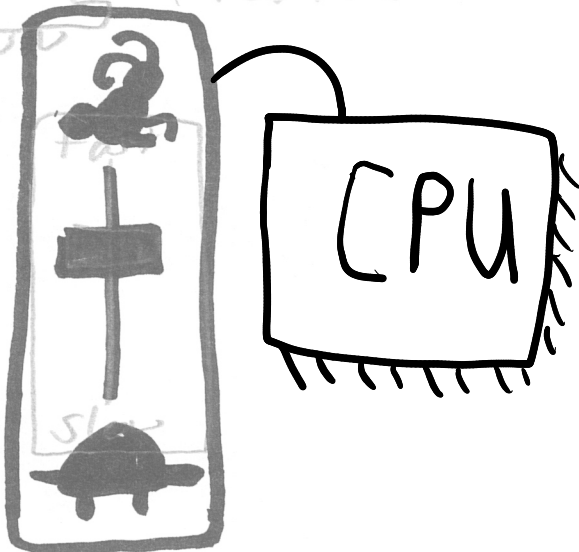
Location



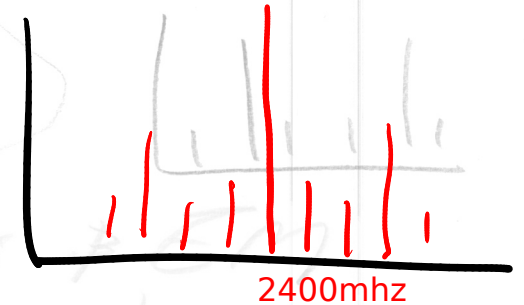
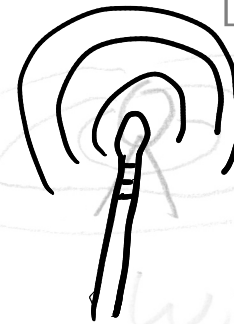
Filesystem and Memory Fragmentation

[Greenawalt et al. 1994]

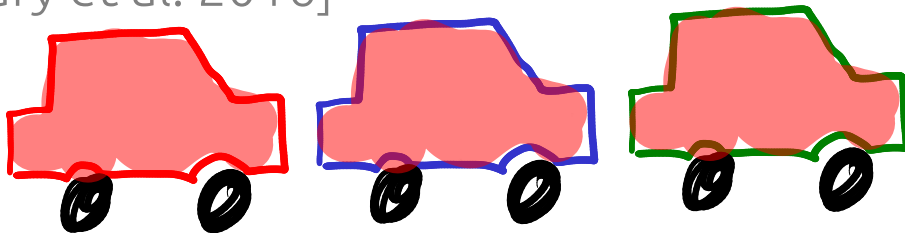
CPU State



[Chowdhury et al. 2016]

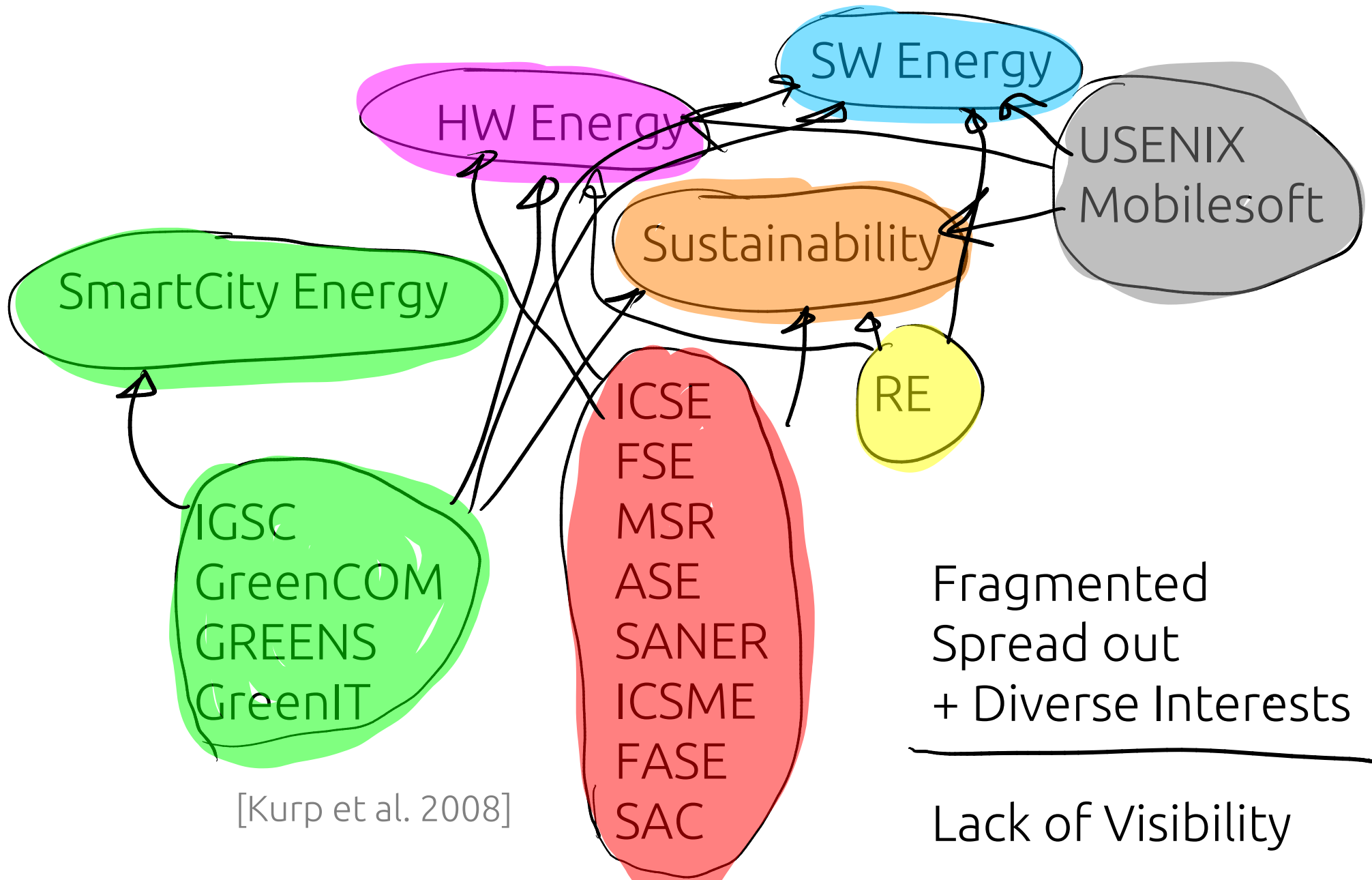


EM non-determinism



Network Congestion

# Community



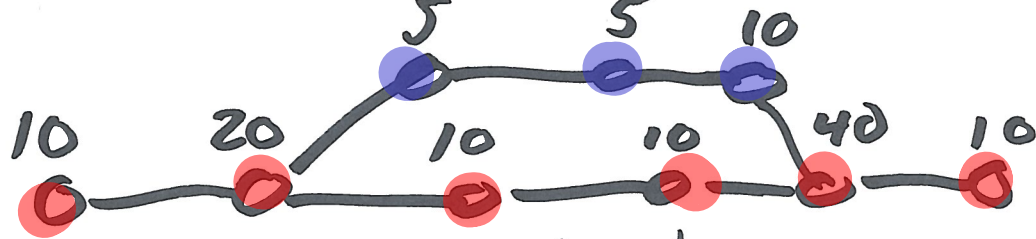
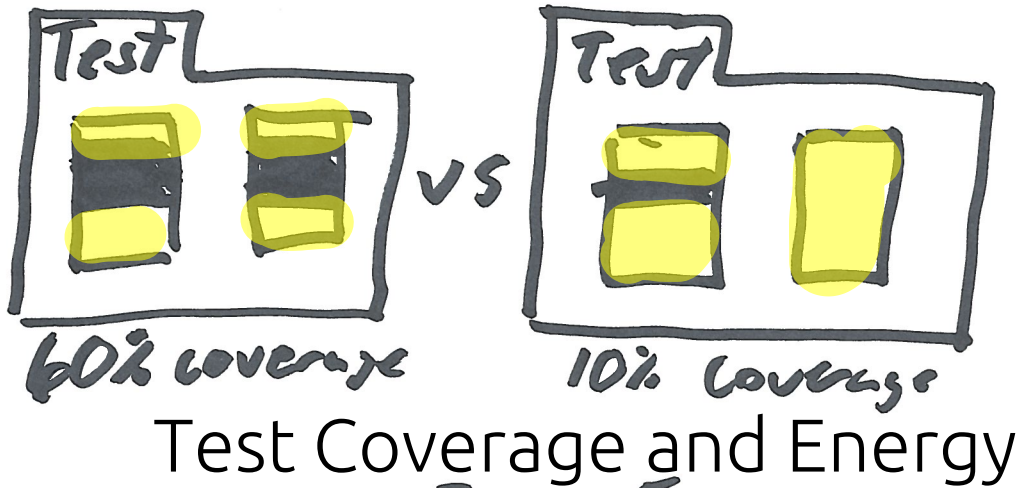
[Kurp et al. 2008]

Fragmented  
Spread out  
+ Diverse Interests

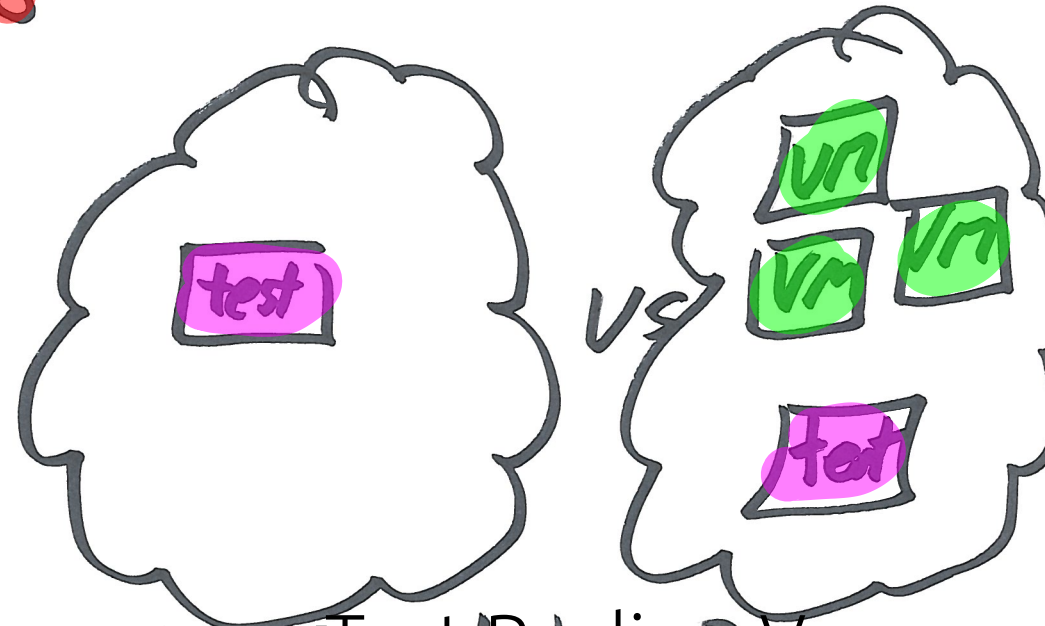
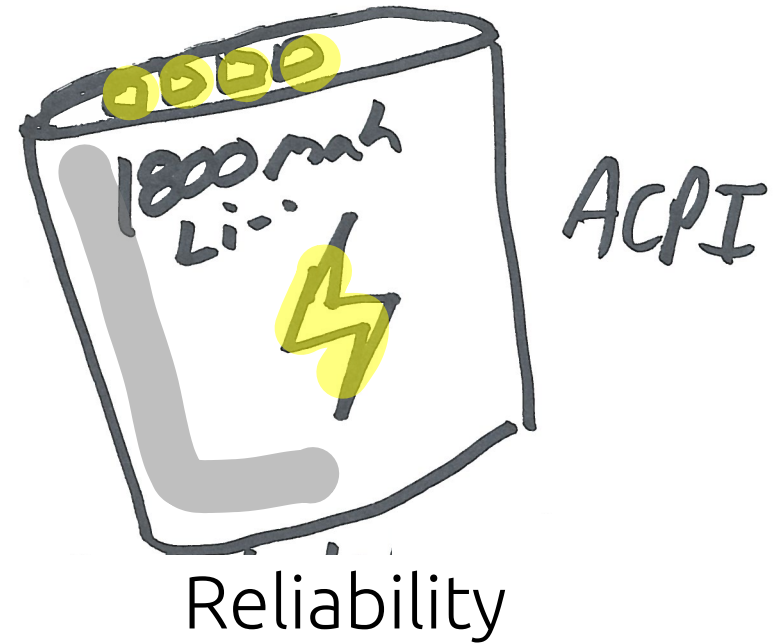
---

Lack of Visibility

# Pitfalls or Papers?



Multi-version testing?  
How much?  
[Romansky et al 2014]

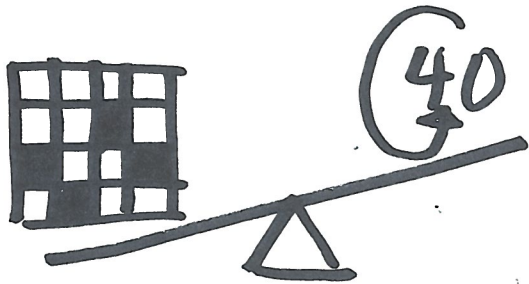


[Moghaddam et al. 2015] Test Realism Versus Test Isolation

# Pitfalls or Paper?

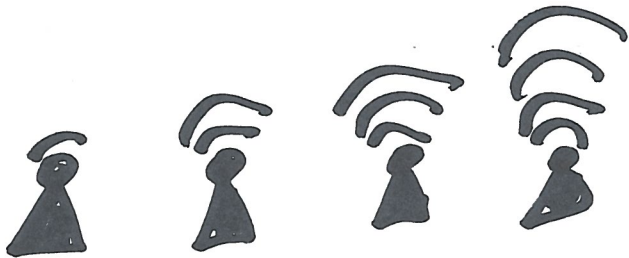


Platform Differences



[Arcuri et al. 2011]

Effects of State  
versus Repeated  
Tests

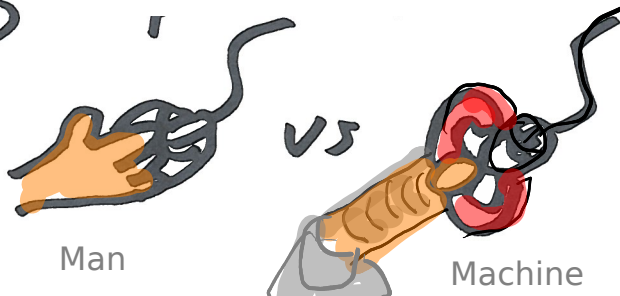


WiFi Effects

Does Fragmentation  
Matter?

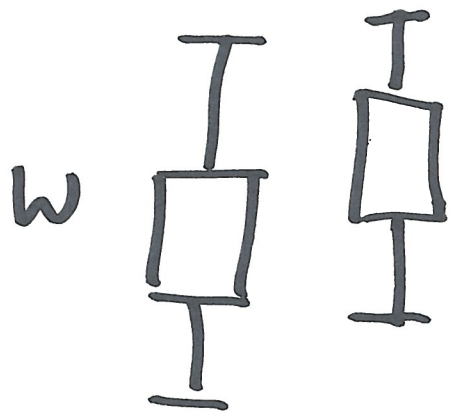


Temperature

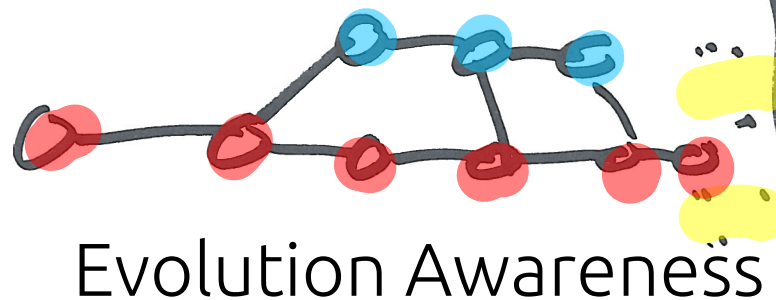


Instrumentation Effects

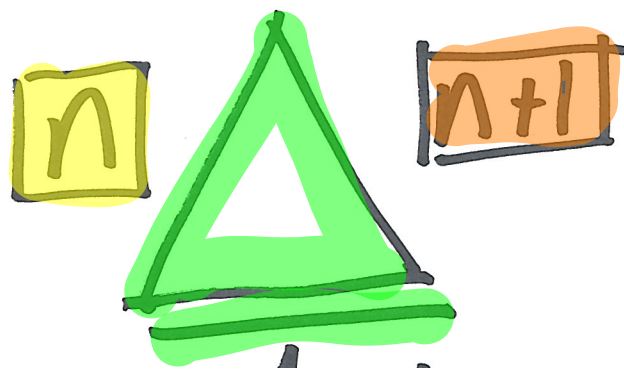
# The Future?



System A & B  
Multiple Runs  
Each

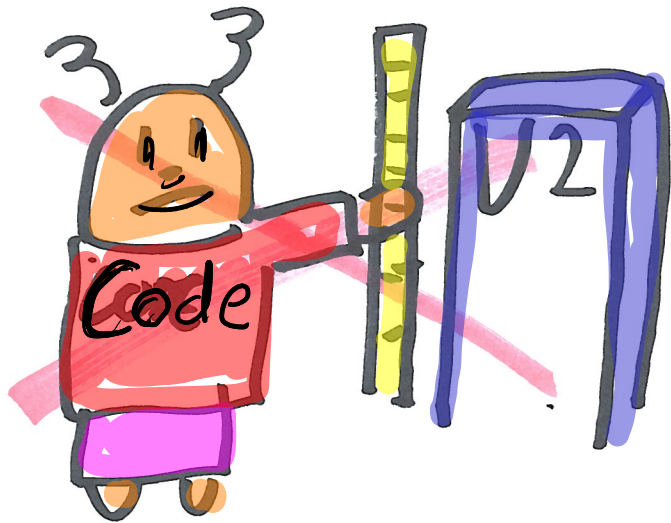


Evolution Awareness



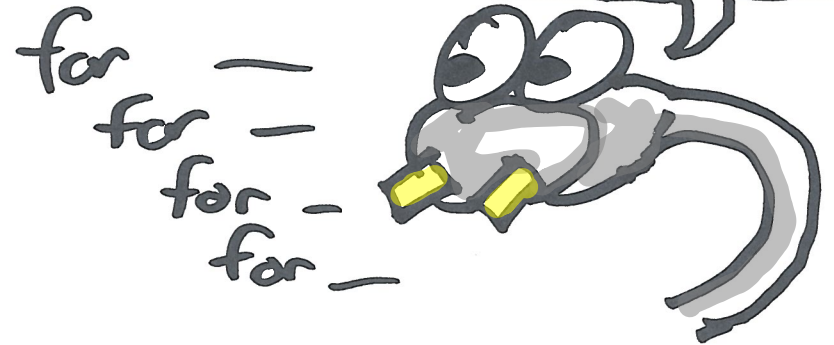
Multiversion Analysis

# Future: Measurement

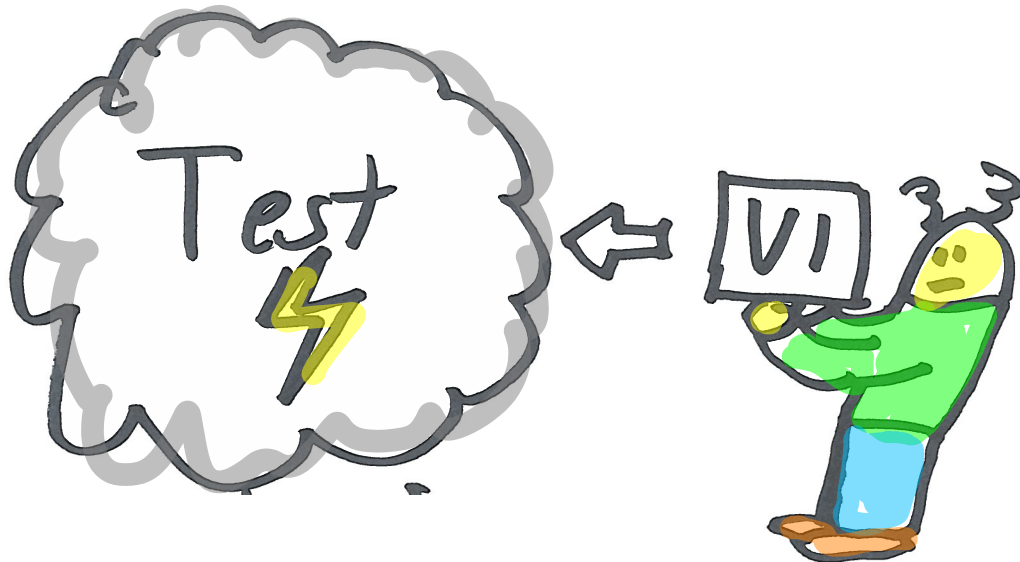


Programmer no longer responsible for measurement

This code could be refactored to save energy



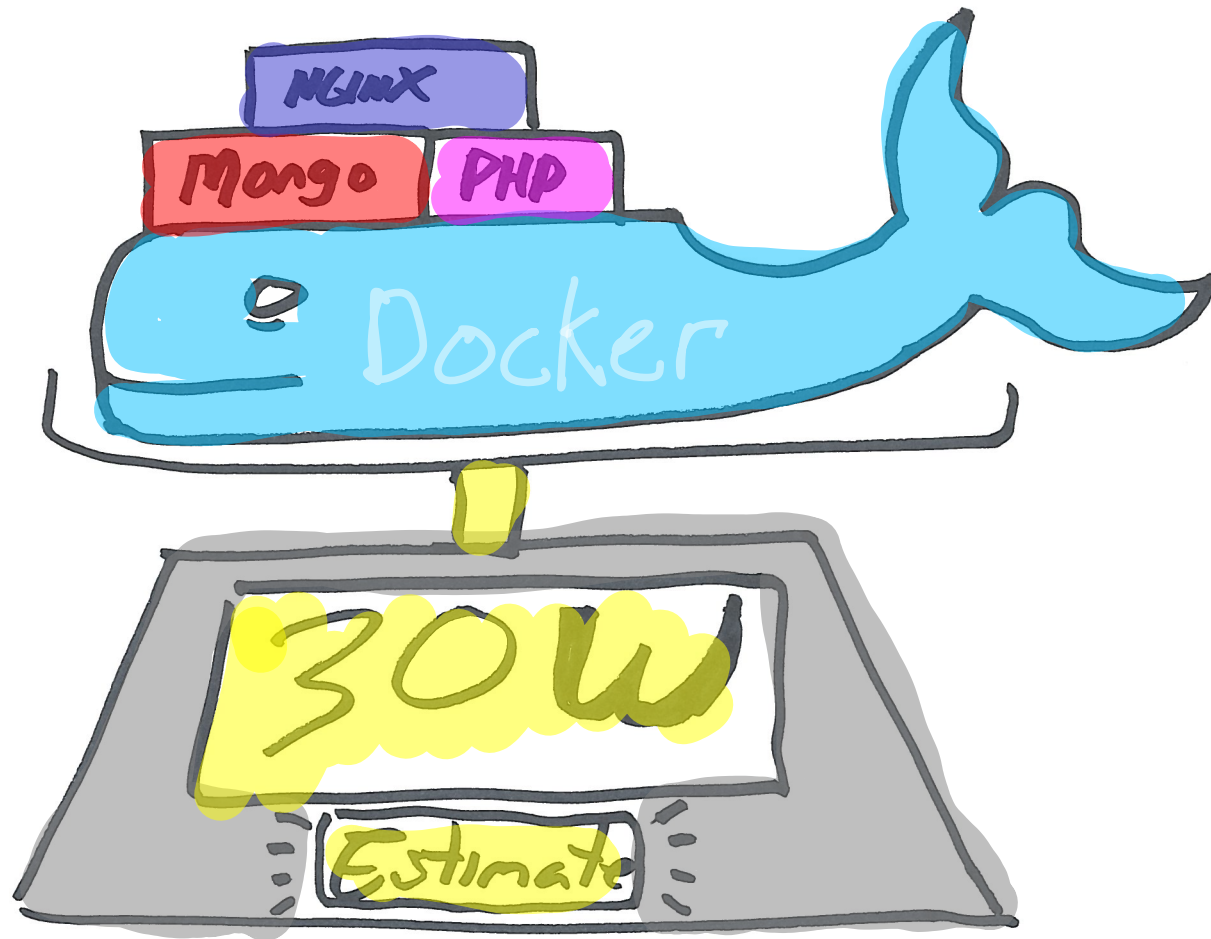
Smart Agents in IDEs



Testing Services



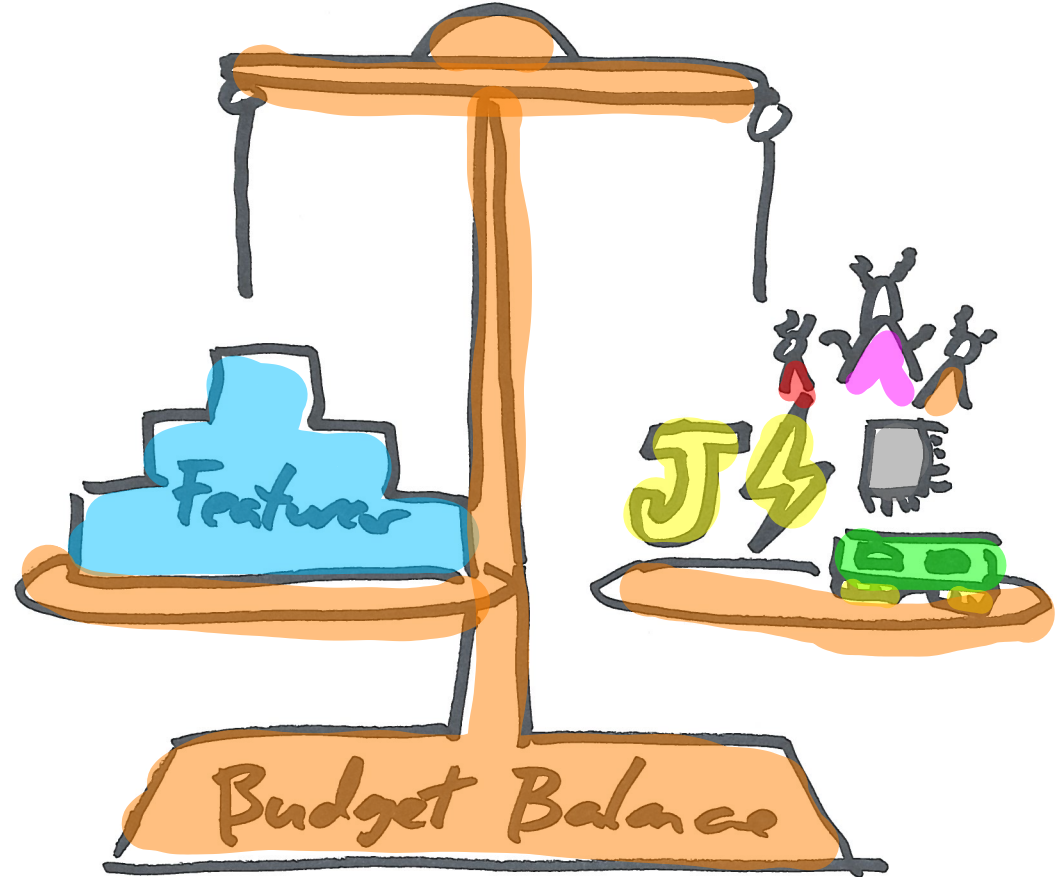
# Cloud and Container Estimation



# Sustainability and Requirements

## Price Chart

IO \$ \_\_\_..--  
CPU \$ \_\_\_..--  
Mem \$ \_\_\_..--  
Net \$ \_\_\_..--  
W \$ \_\_\_..--

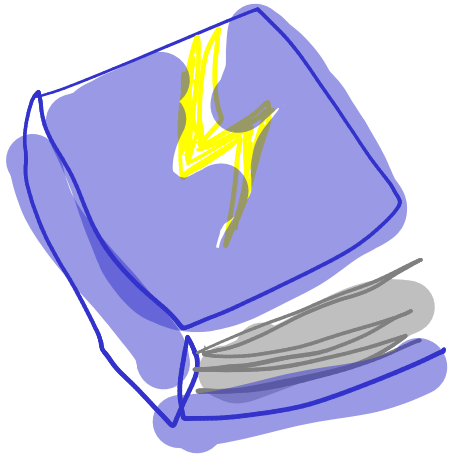


[Becker et al. 2015]

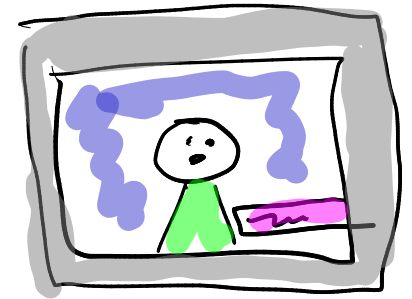
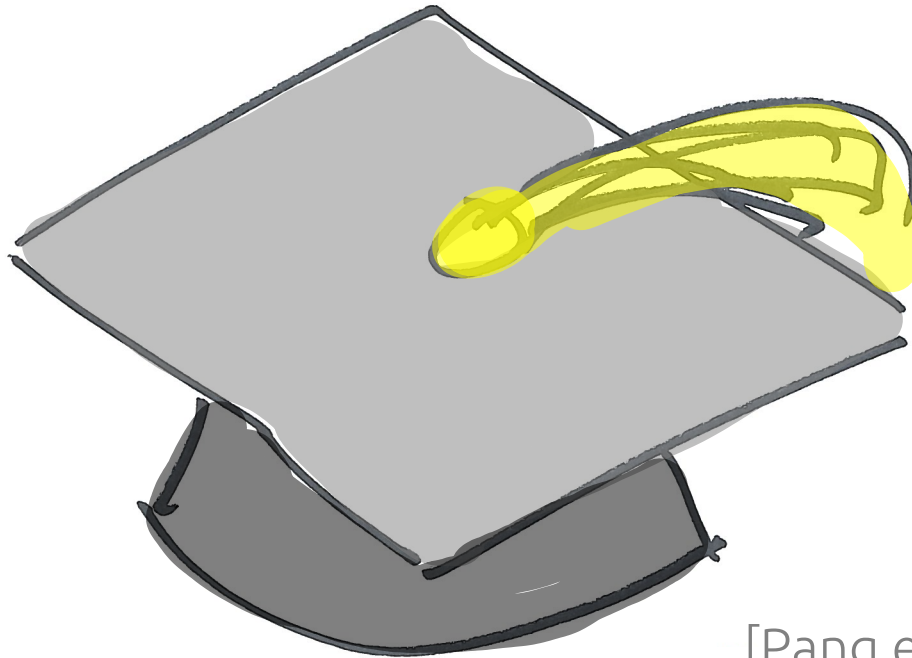
[Lago et al. 2015]



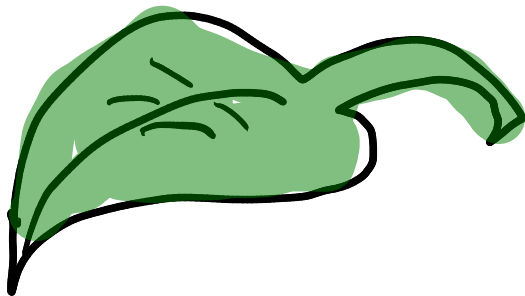
# Education



Text  
Books



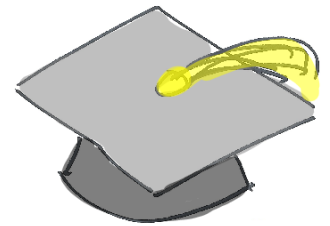
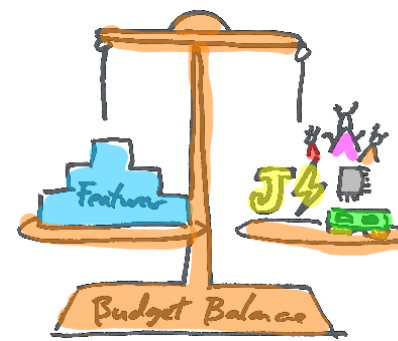
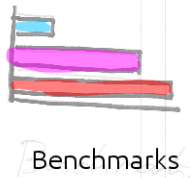
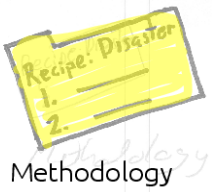
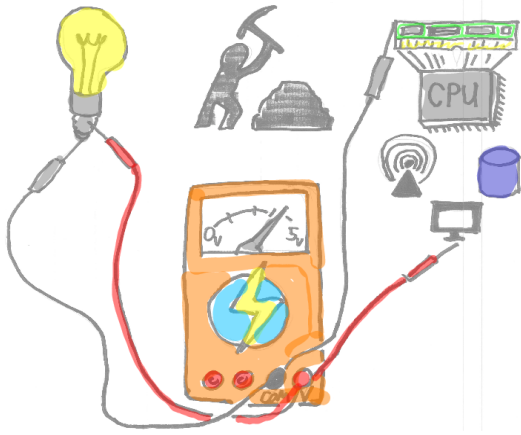
MOOCs  
Syllabi  
Cirrriculum



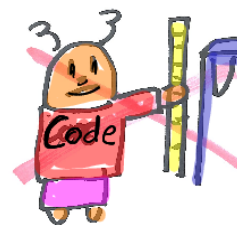
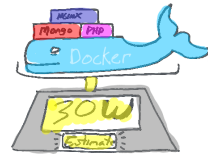
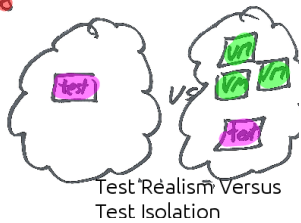
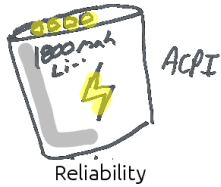
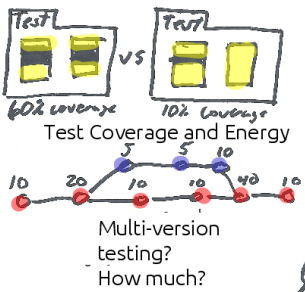
Sustainability

[Pang et al. 2015]  
[Pinto et al. 2014]  
[Wilke et al. 2013]  
[Khalid et al. 2014]  
[Kurp et al. 2008]

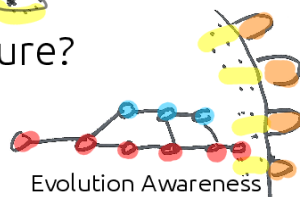
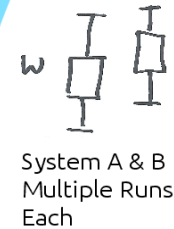
# Conclusions







## Pitfalls or Papers?




## The Future?




Multiversion Analysis

-  **Andrea Arcuri and Lionel Briand.**  
A practical guide for using statistical tests to assess randomized algorithms in software engineering.  
*In Software Engineering (ICSE), 2011 33rd International Conference on, pages 1–10. IEEE, 2011.*
-  **Karan Aggarwal, Abram Hindle, and Eleni Stroulia.**  
Greenadvisor: A tool for analyzing the impact of software evolution on energy consumption.  
*In 31st IEEE International Conference on Software Maintenance and Evolution. IEEE Computer Society, 2015.*
-  **Alliance to Save Energy.**  
PC Energy Report 2007: United States.  
Technical report, 1E, 2007.
-  **Nadine Amsel and Bill Tomlinson.**  
Green tracker: a tool for estimating the energy consumption of software.


In *Proceedings, CHI EA*, pages 3337–3342, New York, NY, USA, 2010. ACM.


-  Karan Aggarwal, Chenlei Zhang, Joshua Charles Campbell, Abram Hindle, and Eleni Stroulia.  
The power of system call traces: Predicting the software energy consumption impact of changes.  
*In Press of the 2014 Conference of the Center for Advanced Studies on Collaborative Research, IBM Corp*, 2014.





-  Abhijeet Banerjee, Lee Kee Chong, Sudipta Chattopadhyay, and Abhik Roychoudhury.  
Detecting energy bugs and hotspots in mobile apps.  
*In Proceedings of the 22nd ACM SIGSOFT International Symposium on Foundations of Software Engineering*, pages 588–598. ACM, 2014.

-  Christoph Becker, Ruzanna Chitchyan, Leticia Duboc, Steve Easterbrook, Birgit Penzenstadler, Norbert Seyff, and Colin C. Venters.

Sustainability design and software: The karlskrona manifesto.  
In *37th IEEE/ACM International Conference on Software Engineering, ICSE 2015, Florence, Italy, May 16-24, 2015, Volume 2*, pages 467–476. IEEE, 2015.

 Bobby R. Bruce, Justyna Petke, and Mark Harman.  
Reducing energy consumption using genetic improvement.  
In *Proceedings of the 2015 Annual Conference on Genetic and Evolutionary Computation, GECCO '15*, pages 1327–1334, New York, NY, USA, 2015. ACM.

 Shaiful Alam Chowdhury, Luke N Kumar, Md. Toukir Imam  
Mohomed Shazan Mohomed Jabbar, Varun Sapra, Karan  
Aggarwal, Abram Hindle, and Russell Greiner.  
A system-call based model of software energy consumption  
without hardware instrumentation.  
In *Proceedings of the Sixth International Green and Sustainable Computing Conference (IGSC'15)*, 2015.



-  Maelick Claes, Tom Mens, Roberto Di Cosmo, and Jérôme Vouillon.  
A historical analysis of debian package incompatibilities.  
*In Mining Software Repositories (MSR), 2015 IEEE/ACM 12th Working Conference on*, pages 212–223. IEEE, 2015.
-  Shaiful Alam Chowdhury, Varun Sapra, and Abram Hindle.  
Is HTTP/2 more energy efficient than HTTP/1.1 for mobile users?  
*PeerJ PrePrints*, 3:e1280, 2015.
-  *International Symposium on Empirical Software Engineering and Measurement*, 2015.
-  Jiaping Gui, Stuart Mcilroy, Meiyappan Nagappan, and William G. J. Halfond.  
Truth in advertising: The hidden cost of mobile ads for software developers.




In *37th IEEE/ACM International Conference on Software Engineering, ICSE 2015, Florence, Italy, May 16-24, 2015, Volume 1*, pages 100–110. IEEE, 2015.

-  P.M. Greenawalt.  
Modeling power management for hard disks.  
In *MASCOTS '94., Proceedings of the Second International Workshop on*, pages 62 –66, Jan 1994.
-  *GREENCOM '12: Proceedings of the 2012 IEEE International Conference on Green Computing and Communications*, Washington, DC, USA, 2012. IEEE Computer Society.
-  Fourth international workshop on green and sustainable software (GREENS 2015).  
2015.
-  Ashish Gupta, Thomas Zimmermann, Christian Bird, Nachippan Naggapan, Thirumalesh Bhat, and Syed Emran.  
Energy Consumption in Windows Phone.


Technical Report MSR-TR-2011-106, Microsoft Research, 2011.


-  **Ahmed E. Hassan.**  
The Road Ahead for Mining Software Repositories.  
*In Proceedings of the Future of Software Maintenance (FoSM) at the 24th IEEE International Conference on Software Maintenance*, pages 48–57, 2008.
-  **Eric Horvitz, Jack Breese, David Heckerman, David Hovel, and Koos Rommelse.**  
The lumiere project: Bayesian user modeling for inferring the goals and needs of software users.  
*In Proceedings of the Fourteenth conference on Uncertainty in artificial intelligence*, pages 256–265. Morgan Kaufmann Publishers Inc., 1998.
-  **Abram Hindle.**  
Green mining: A methodology of relating software change to power consumption.

In Submission to MSR 2012,  
<http://softwareprocess.es/a/green-change-e.pdf>.

-  Abram Hindle.  
Green mining: Investigating power consumption across versions.  
In *Proceedings, ICSE: NIER Track*. IEEE Computer Society, 2012.

<http://ur1.ca/84vh4>.

-  Abram Hindle.  
Green mining: a methodology of relating software change and configuration to power consumption.  
*Empirical Software Engineering*, 20(2):374–409, 2015.

-  Shuai Hao, Ding Li, William G. J. Halfond, and Ramesh Govindan.  
Estimating Mobile Application Energy Consumption using Program Analysis.

*In Proceedings of the 2013 International Conference on Software Engineering, ICSE '13, pages 92–101, 2013.*

 Abram Hindle, Alex Wilson, Kent Rasmussen, Jed Barlow, Joshua Campbell, and Stephen Romansky.

GreenMiner: A Hardware Based Mining Software Repositories Software Energy Consumption Framework.

*In Mining Software Repositories (MSR), 2014 11th IEEE Working Conference on. ACM, 2014.*

 Dan Han, Chenlei Zhang, Xiaochao Fan, A. Hindle, K. Wong, and E. Stroulia.

Understanding android fragmentation with topic analysis of vendor-specific bugs.

*In Reverse Engineering (WCRE), 2012 19th Working Conference on, pages 83–92, Oct 2012.*

 *Proceedings of the Sixth International Green and Sustainable Computing Conference (IGSC'15), 2015.*



Intel.

LessWatts.org - Saving Power on Intel systems with Linux.

<http://www.lesswatts.org>, 2011.



Abram Hindle Ivanilton Polato, Denilson Barbosa and Fabio Kon.

Hadoop branching: Architectural impacts on energy and performance.

*In Proceedings of the Sixth International Green and Sustainable Computing Conference (IGSC'15), 2015.*



Russ Joseph and Margaret Martonosi.

Run-Time Power Estimation in High Performance Microprocessors.

*In Proceedings of the 2001 international symposium on Low power electronics and design, ISLPED '01, pages 135–140, New York, NY, USA, 2001. ACM.*



Matthew Eastwood Jed Scaramella.

Solutions for the datacenter's thermal challenges.

<http://whitepapers.zdnet.com/abstract.aspx?docid=352318>,  
January 2007.

IDC white paper.



Reyhaneh Jabbarvand, Alireza Sadeghi, Joshua Garcia, Sam Malek, and Paul Ammann.

Ecodroid: an approach for energy-based ranking of android apps.  
*In Proceedings of the Fourth International Workshop on Green and Sustainable Software*, pages 8–14. IEEE Press, 2015.



Hammad Khalid, Emad Shihab, Meiyappan Nagappan, and Ahmed E Hassan.

What do mobile app users complain about? A study on free iOS apps.

*Accepted to be published in IEEE Software*, 2014.




Patrick Kurp.

Green computing.

*Communications of the ACM*, 51(10):11–13, 2008.

-  Ding Li, Shuai Hao, Jiaping Gui, and William G. J. Halfond.  
An empirical study of the energy consumption of android applications.  
*In 30th IEEE International Conference on Software Maintenance and Evolution, Victoria, BC, Canada, September 29 - October 3, 2014*, pages 121–130. IEEE Computer Society, 2014.
-  Ding Li, Shuai Hao, William GJ Halfond, and Ramesh Govindan.  
Calculating source line level energy information for android applications.  
*In Proceedings of the 2013 International Symposium on Software Testing and Analysis*, pages 78–89. ACM, 2013.
-  Patricia Lago, Sedef Akinli Koçak, Ivica Crnkovic, and Birgit Penzenstadler.  
Framing sustainability as a property of software quality.  
*Commun. ACM*, 58(10):70–78, 2015.

 Mario Linares-Vásquez, Gabriele Bavota, Carlos Bernal-Cárdenas, Rocco Oliveto, Massimiliano Di Penta, and Denys Poshyvanyk. Mining energy-greedy api usage patterns in android apps: An empirical study.

*In Proceedings of the 11th Working Conference on Mining Software Repositories, MSR 2014, pages 2–11, New York, NY, USA, 2014. ACM.*

 Mario Linares-Vásquez, Gabriele Bavota, Carlos Eduardo Bernal Cárdenas, Rocco Oliveto, Massimiliano Di Penta, and Denys Poshyvanyk.

Optimizing energy consumption of guis in android apps: A multi-objective approach.

*In Proceedings of the 2015 10th Joint Meeting on Foundations of Software Engineering, ESEC/FSE 2015, pages 143–154, New York, NY, USA, 2015. ACM.*

 Y. Liu, C. Xu, and S. Cheung.



Diagnosing energy efficiency and performance for mobile internetware applications: Challenges and opportunities.  
*Software, IEEE*, PP(99):1–1, 2015.


 Fahimeh Alizadeh Moghaddam, Thomas Geenen, Patricia Lago, and Paola Grosso.

A user perspective on energy profiling tools in large scale computing environments.


*In 2015 Sustainable Internet and ICT for Sustainability, SustainIT 2015, Madrid, Spain, April 14-15, 2015*, pages 1–5. IEEE, 2015.

 Tim Menzies, R. Krishna, and D. Pryor.

The promise repository of empirical software engineering data.  
North Carolina State University, Department of Computer Science, 2016.


 Fahimeh Alizadeh Moghaddam, Patricia Lago, and Paola Grosso.  
Energy-efficient networking solutions in cloud-based environments: A systematic literature review.


*ACM Comput. Surv.*, 47(4):64, 2015.

 Irene Manotas, Lori Pollock, and James Clause.  
Seeds: A software engineer's energy-optimization decision support framework.


*In Proceedings of the 36th International Conference on Software Engineering, ICSE 2014*, pages 503–514, New York, NY, USA, 2014. ACM.


 MSR.  
Mining Software Repositories.  
[www.msrconf.org](http://www.msrconf.org), 2013.


 San Murugesan.  
Harnessing Green IT: Principles and Practices.  
*IT Professional*, 10(1):24–33, 2008.

 Gustavo Pinto, Fernando Castor, and Yu David Liu.  
Mining questions about software energy consumption.

In *Proceedings of the 11th Working Conference on Mining Software Repositories*, pages 22–31. ACM, 2014.

 Candy Pang, Abram Hindle, Bram Adams, and Ahmed E Hassan.  
What do programmers know about the energy consumption of software?  
*IEEE Software*.

 Abhinav Pathak, Y Charlie Hu, and Ming Zhang.  
Bootstrapping energy debugging on smartphones: a first look at energy bugs in mobile devices.  
In *Proceedings of the 10th ACM Workshop on Hot Topics in Networks*, page 5. ACM, 2011.

 E. Peltonen, E. Lagerspetz, P. Nurmi, and S. Tarkoma.  
Energy modeling of system settings: A crowdsourced approach.  
In *Pervasive Computing and Communications (PerCom), 2015 IEEE International Conference on*, pages 37–45, March 2015.

 Stephen Romansky and Abram Hindle.

On improving green mining for energy-aware software analysis.  
*In Press of the 2014 Conference of the Center for Advanced Studies on Collaborative Research, IBM Corp, 2014.*



Stephen Romansky and Abram Hindle.





On improving green mining for energy-aware software analysis.  
*In Proceedings of 24th Annual International Conference on Computer Science and Software Engineering, pages 234–245. IBM Corp., 2014.*







Kent Rasmussen, Alex Wilson, and Abram Hindle.

Green mining: energy consumption of advertisement blocking methods.

*In Hausi A. Müller, Patricia Lago, Maurizio Morisio, Niklaus Meyer, and Giuseppe Scanniello, editors, Proceedings of the 3rd International Workshop on Green and Sustainable Software, GREENS 2014, Hyderabad, India, June 1, 2014, pages 38–45. ACM, 2014.*

-  Chiyong Seo, Sam Malek, and Nenad Medvidovic.  
An Energy Consumption Framework for Distributed Java-Based Systems.  
In *ASE '07*, pages 421–424, 2007.
-  Chiyong Seo, Sam Malek, and Nenad Medvidovic.  
Component-level energy consumption estimation for distributed java-based software systems.  
In *Component-Based Software Engineering*, pages 97–113.  
Springer, 2008.
-  Cagri Sahin, Lori Pollock, and James Clause.  
How do code refactorings affect energy usage?  
In *Proceedings of the 8th ACM/IEEE International Symposium on Empirical Software Engineering and Measurement, ESEM '14*, pages 36:1–36:10, New York, NY, USA, 2014. ACM.
-  Stack Overflow.  
<http://stackoverflow.com>, 2008.

-  Energy Star.  
Energy star: The simple choice for energy efficiency, 2016.
-  Vivek Tiwari, Sharad Malik, Andrew Wolfe, and Mike Tien-Chien Lee.  
Instruction level power analysis and optimization of software.  
*The Journal of VLSI Signal Processing*, 13, 1996.
-  Claas Wilke, Sebastian Richly, S Gotz, Christian Piechnick, and Uwe Aßmann.  
Energy consumption and efficiency in mobile applications: A user feedback study.  
In *Green Computing and Communications (GreenCom), 2013 IEEE and Internet of Things (iThings/CPSCoM), IEEE International Conference on and IEEE Cyber, Physical and Social Computing*, pages 134–141. IEEE, 2013.
-  Chenlei Zhang and Abram Hindle.

A green miner's dataset: mining the impact of software change on energy consumption.

*In Proceedings of the 11th Working Conference on Mining Software Repositories*, pages 400–403. ACM, 2014.



Chenlei Zhang.

The Impact of User Choice and Software Change and Energy Consumption.

*University of Alberta, Edmonton, Alberta, Canada*, 2013.



Chenlei Zhang, Abram Hindle, and Daniel M. Germán.

The impact of user choice on energy consumption.

*IEEE Software*, 31(3):69–75, 2014.