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Energy Driven Computing:

Rethinking the Design of Energy Harvesting Systems

Geoff Merrett
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Graceful
EPSRC
Pioneering research and skills

Power Sources

- We've got batteries!
  - So what's the problem?
- More things = batteries/wires/people
  - Pervasive/IoT/ubiquitous
- Fit-and-forget/maintenance issues
  - Smart homes/grid/metering
- Weight vs volume vs lifetime
  - e.g. Wearables

image: RS fabrications, http://www.rsfabrications.com/wp-content/uploads/2009/09/cimg2821.jpg
image: http://commons.wikimedia.org/wiki/File:Canary_Wharf_at_night,_from_Shadwell_cropped.jpg
image: Australian Transport Safety Bureau, http://www.atsb.gov.au/media/2489702/ro2010001.jpg
image: Kirk Martinez and Phil Basford, Glacsweb project, University of Southampton

Energy harvesting sources

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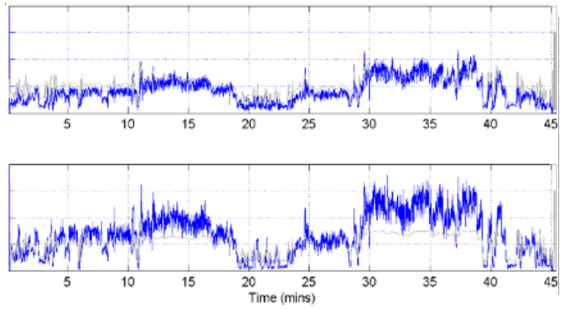
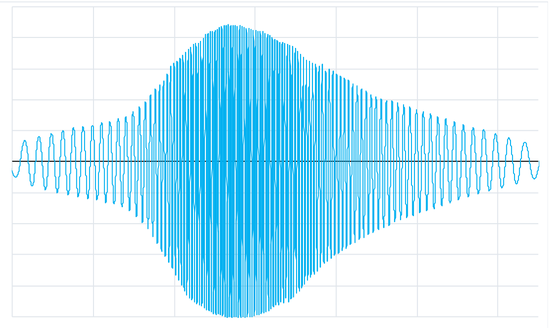
Geoff V Merrett, "*Energy Driven Computing: Rethinking the Design of Energy Harvesting Systems*", DATE 2017

varies temporally



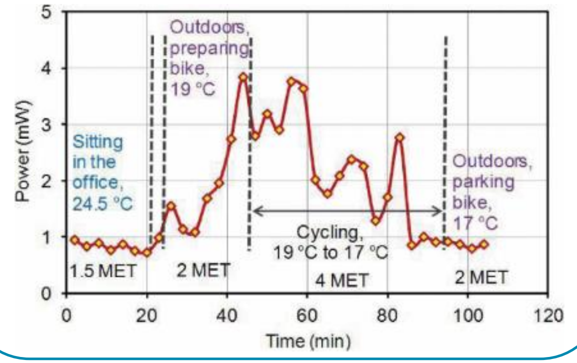
Beeby, S.P. et al. A comparison of power output from linear and non-linear kinetic energy harvesters using real vibration data. Smart Materials and Structures, 22, (7), 075022.



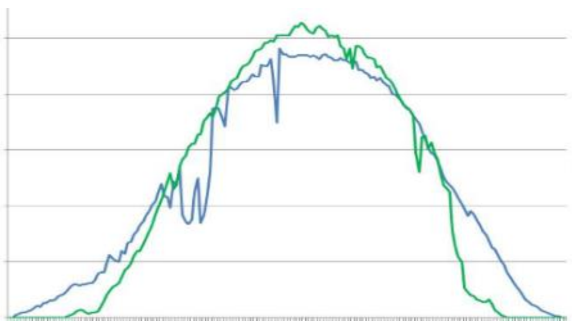
D. Balsamo et al. Hibernus++: a self-calibrating and adaptive system for transiently-powered embedded devices. IEEE TCAD, 1-13.

Power / Energy

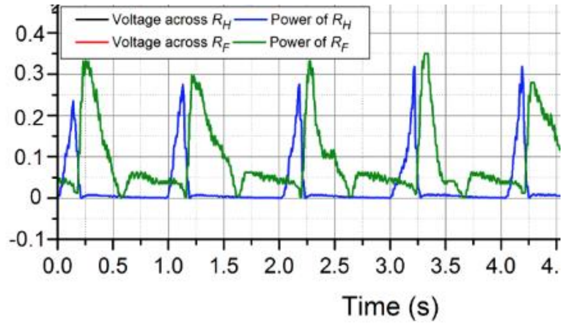
varies spatially



V. Leonov, "Thermoelectric Energy Harvesting of Human Body Heat for Wearable Sensors," IEEE Sensors Journal, vol.13, no.6, pp.2284-91, June13



http://solar.rainham-kent.co.uk



Zhao, J. et al. "A Shoe-Embedded Piezoelectric Energy Harvester for Wearable Sensors," Sensors 2014, 14, 12497-12510.

Highly variable supply + variable consumption!

Powering systems from harvested energy

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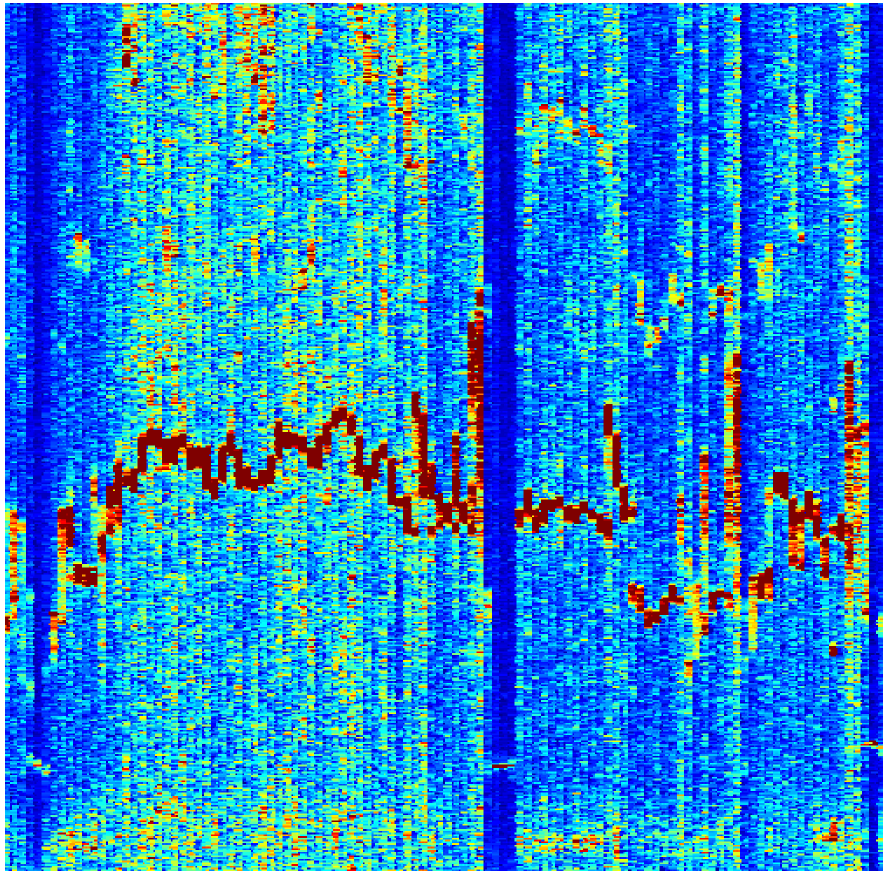
Geoff V Merrett, "*Energy Driven Computing: Rethinking the Design of Energy Harvesting Systems*", DATE 2017

- Energy-Harvesting Systems
- Energy-Neutral Computing
- Transient Computing
- Power-Neutral Computing

Energy-Driven Systems



Energy-Neutral Computing

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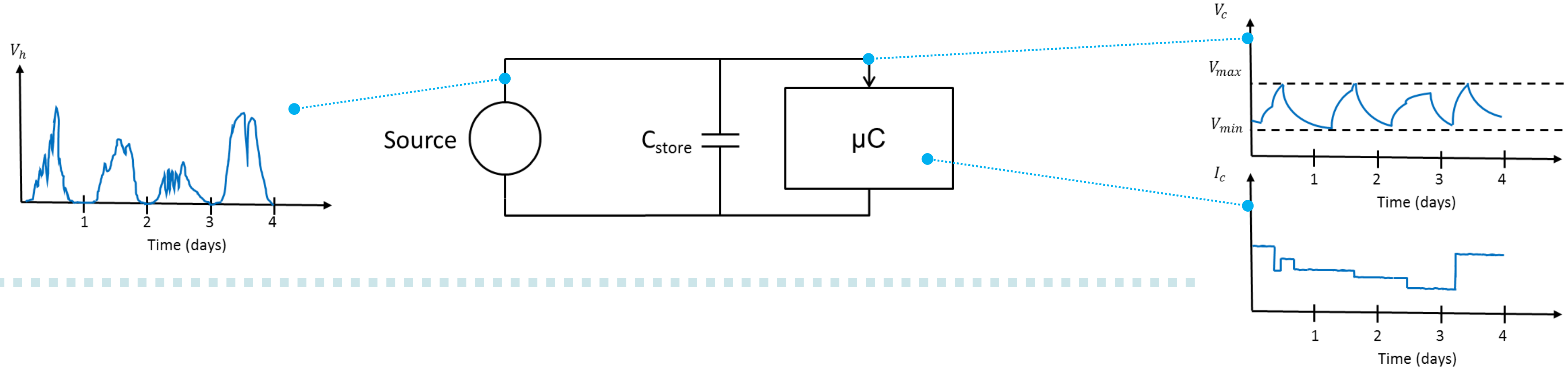
Schematic



Block Diagram

Power Supply → Power Conversion → Energy Storage → Power Conversion → Computation (Load)

$$\int_{(n-1)\cdot T}^{n\cdot T} P_h(t)dt = \int_{(n-1)\cdot T}^{n\cdot T} P_c(t)dt$$

Stored Energy

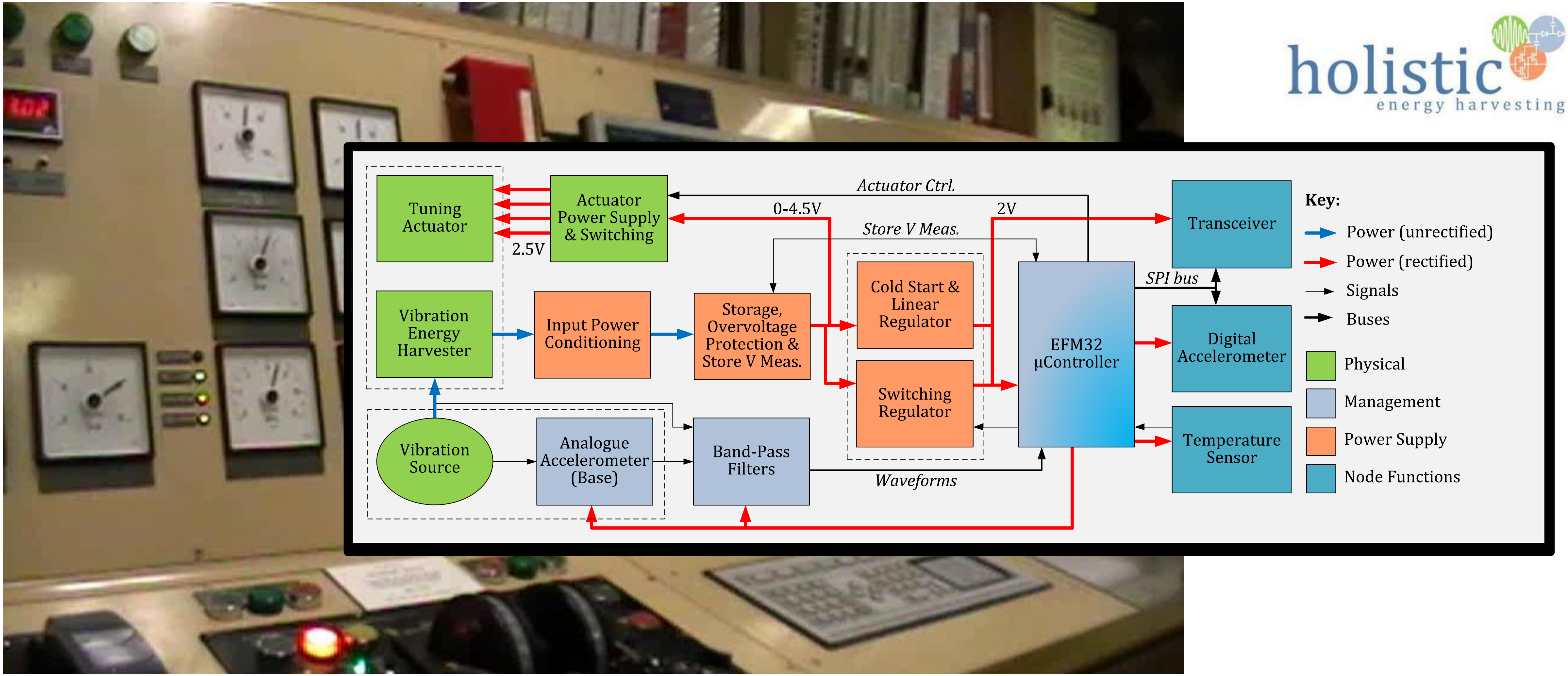
Energy Harvesting Case Study

holistic energy harvesting

A.S. Weddell, D. Zhu, G.V. Merrett, S.P. Beeby, B.M. Al-Hashimi, (2012) A practical self-powered sensor system with a tunable vibration energy harvester. In, PowerMEMS 2012, Atlanta, US, 02 - 05 Dec 2012.

Energy Harvesting Case Study

Geoff V Merrett, "*Energy Driven Computing: Rethinking the Design of Energy Harvesting Systems*", DATE 2017



A.S. Weddell, D. Zhu, G.V. Merrett, S.P. Beeby, B.M. Al-Hashimi, (2012) A practical self-powered sensor system with a tunable vibration energy harvester. In, PowerMEMS 2012, Atlanta, US, 02 - 05 Dec 2012.

Transient Computing: Motivation

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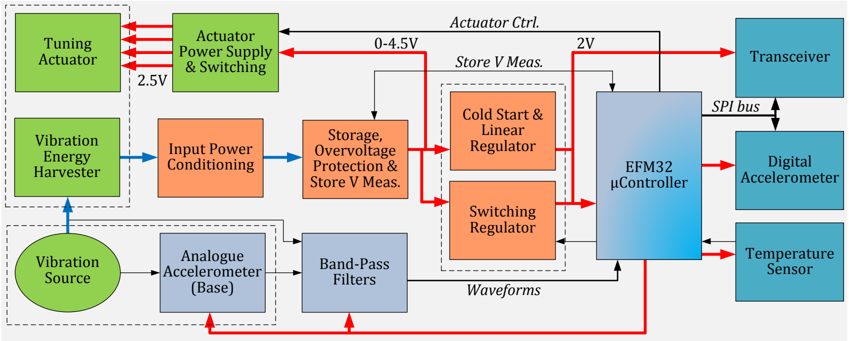
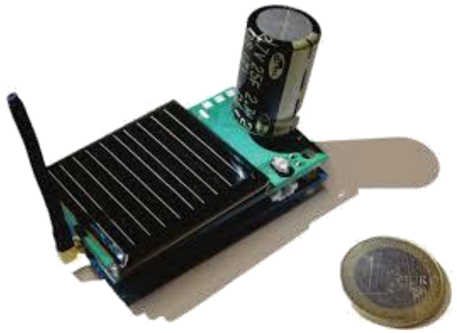
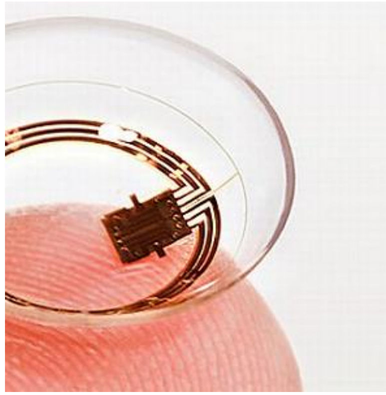
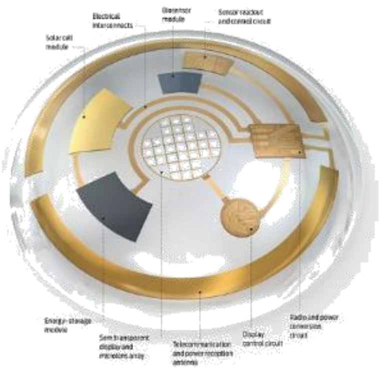
- What's wrong with energy storage and complexity?





- Emerging applications demanding small dimensions, volumes, weight, cost, etc





Transient Computing: Introduction

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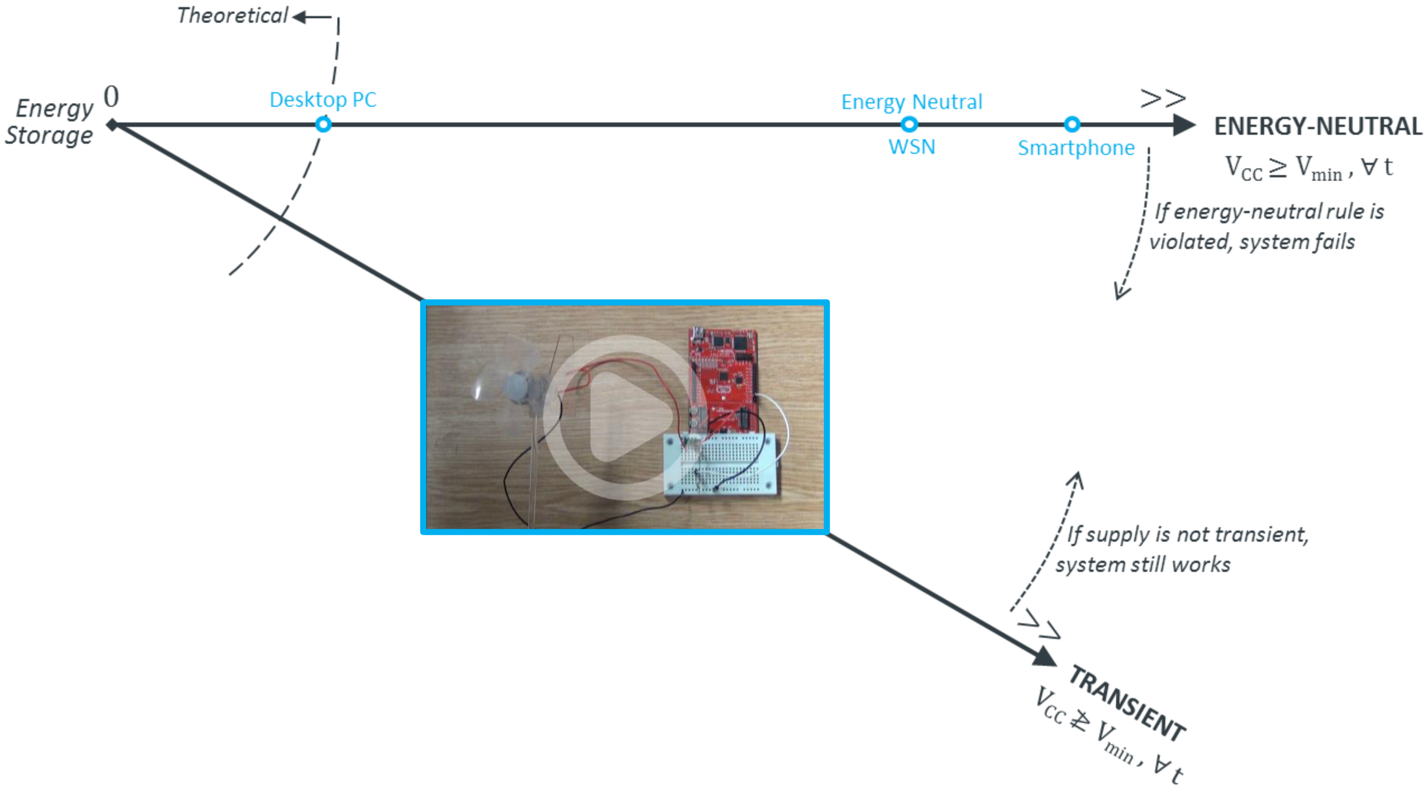
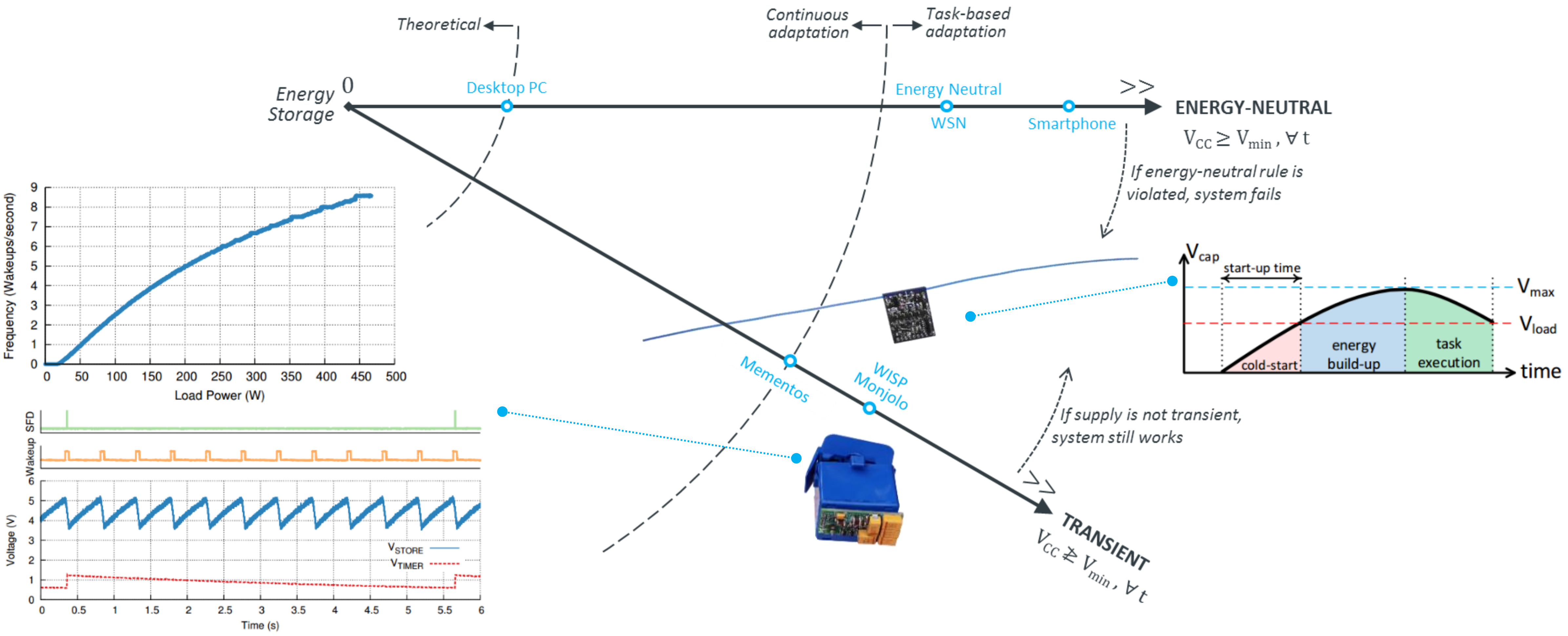
Block Diagram

Stored Energy



Transient Computing: Existing Systems

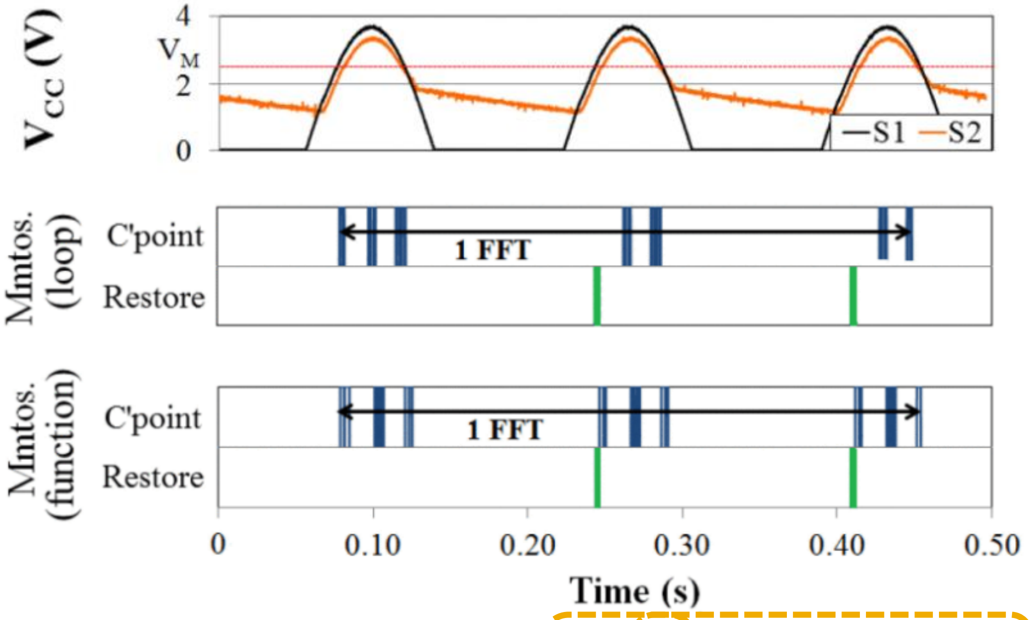


Monjolo: S. DeBruin et al., Monjolo: An Energy-Harvesting Energy Meter Architecture, ACM SenSys'13
A. Gomez et al., "Dynamic energy burst scaling for transiently powered systems," *DATE 2016*, Dresden, 2016, pp. 349-354.
WISP: A. P. Sample et a., "Design of an RFID-Based Battery-Free Programmable Sensing Platform," in IEEE Transactions on Instrumentation and Measurement, vol. 57, no. 11, pp. 2608-2615, Nov. 2008.
Mementos: B. A. Ransford, J. M. Sorber and K. Fu, “Mementos: System Support for Long-Running Computation on RFID-Scale Devices”, *ASPLOS’11*, March 5–11, 2011, Newport Beach, California, USA.

Mementos

Geoff V Merrett, "*Energy Driven Computing: Rethinking the Design of Energy Harvesting Systems*", DATE 2017

- Early work in transient computing
  - Uses concept of check pointing (from fault tolerance) to NVM; a design/compile-time approach
- Checkpoint placement
  - Heuristics, e.g. start of loop/function
  - *Redundant checkpoints/snapshots (causing overheads in both t and E)*
- At a checkpoint
  - Snapshot made if V_{CC} < threshold
  - *If V_{CC} << threshold, may not be enough time*
- After an interruption
  - Restores if a valid snapshot was saved
  - *Code executed since last checkpoint re-executed*



$$\underbrace{T_{\text{mementos}}}_{\text{Total execution}} = \overbrace{T_a}^{\text{Algorithm}} + \underbrace{n_\iota}_{\text{No. interruptions}} \Big(\overbrace{T_r}^{\text{Restore snapshot}} + \underbrace{\frac{T_a}{2n_m}}_{\text{Backtrack}} \Big) + \overbrace{n_m(T_m + \rho_s T_s)}^{\text{Monitoring and save snapshot}}$$

Mementos: B. A. Ransford, J. M. Sorber and K. Fu, "Mementos: System Support for Long-Running Computation on RFID-Scale Devices", *ASPLOS'11*, March 5-11, 2011, Newport Beach, California, USA.
Image: D. Balsamo, A. Weddell, A. Das, A. Rodriguez, D. Brunelli, B. Al-Hashimi, G. Merrett, L. Benini, Hibernus++: a self-calibrating and adaptive system for transiently-powered embedded devices. *IEEE TCAD*, 2016.

Hibernus

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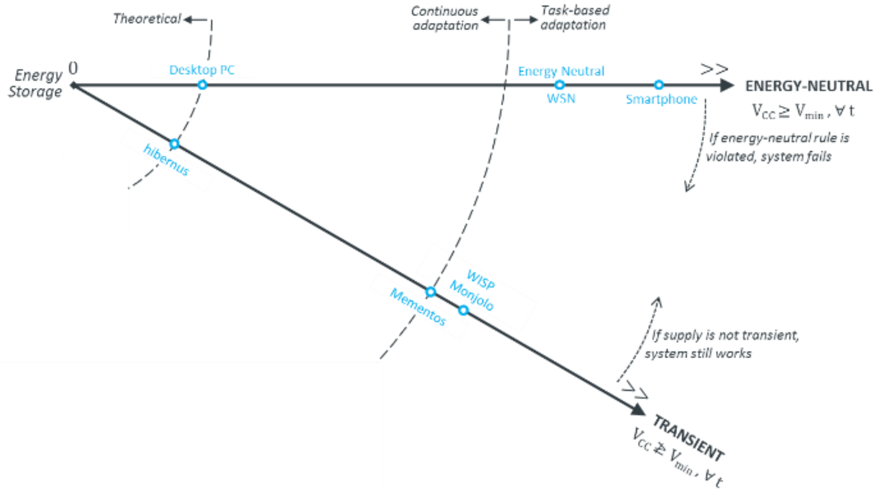
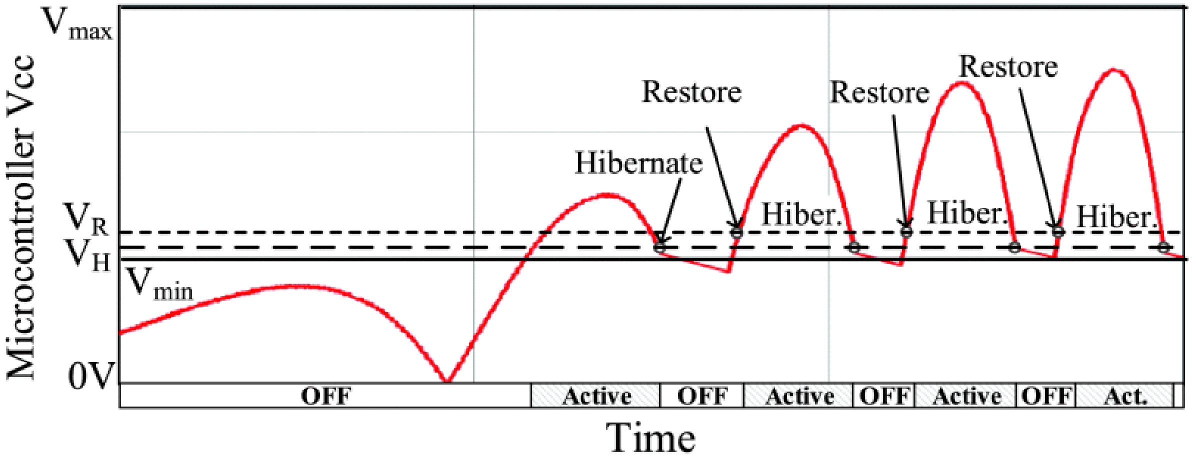
- Runtime approach, makes only a single (and always a single) snapshot per supply 'failure'
  - Removes wasted snapshots (increases efficiency)
  - Ensures that a valid snapshot is always made (improves reliability)

$$\underbrace{T_{\text{Hibernus}}}_{\text{Total execution}} = \overbrace{T_a}^{\text{Algorithm}} + \underbrace{n_\iota}_{\text{No. interruptions}} (\overbrace{T_s}^{\text{Save snapshot}} + \underbrace{T_r}_{\text{Restore snapshot}} + \overbrace{T_\lambda}^{\text{Sleep}})$$

- Make it as late as possible
  - Avoids re-executing code (increases efficiency)
  - Maximises execution time (increases efficiency)

$$\underbrace{T_{\text{mementos}}}_{\text{Total execution}} = \overbrace{T_a}^{\text{Algorithm}} + \underbrace{n_\iota}_{\text{No. interruptions}} (\overbrace{T_r}^{\text{Restore snapshot}} + \underbrace{\frac{T_a}{2n_m}}_{\text{Backtrack}}) + \overbrace{n_m(T_m + \rho_s T_s)}^{\text{Monitoring and save snapshot}}$$



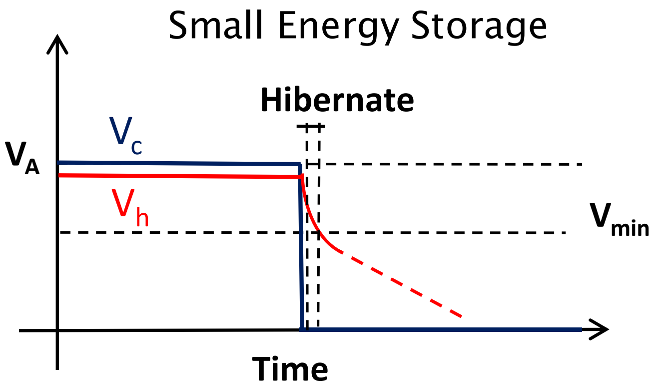


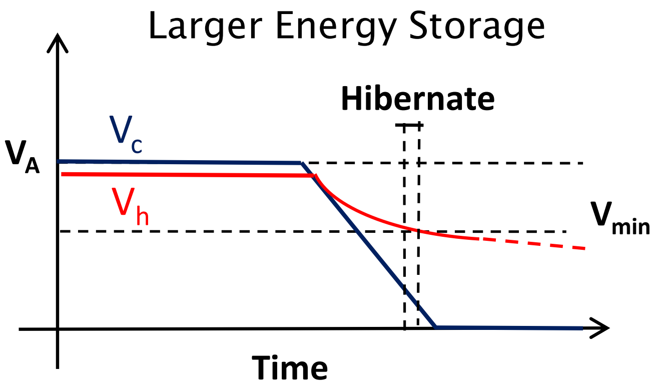
D. Balsamo, A.S. Weddell, G.V. Merrett, B.M. Al-Hashimi, D. Brunelli, and L. Benini, "Hibernus: Sustaining Computation during Intermittent Supply for Energy-Harvesting Systems," IEEE Embedded Systems Letters, 2014

Hibernus: When to hibernate and restore?

- *Hibernus* requires calibration of the platform and energy source:
  - Select hibernate threshold based on $\sum C$ (Platform Dependent; static)
  - Select restore threshold based on source dynamics (Source Dependent; adaptive)
- *Hibernus* performs adaptive, run-time calibration and management
- Hibernate threshold calibration

$$n_\alpha E_\alpha + n_\beta E_\beta \leq \frac{V_H^2 - V_{min}^2}{2} \sum C$$





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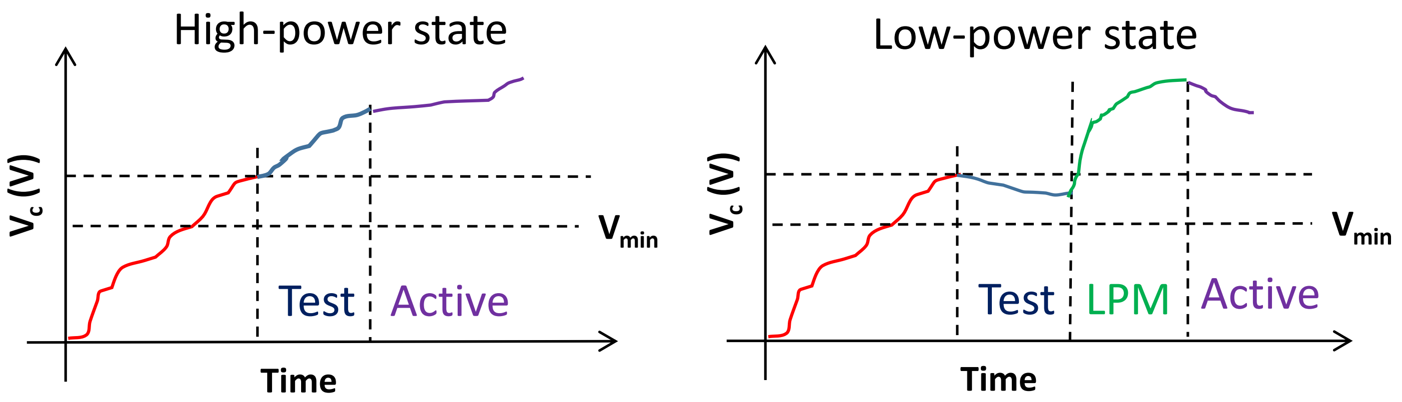
  - Select hibernate threshold based on $\sum C$ (Platform Dependent; static)
  - Select restore threshold based on source dynamics (Source Dependent; adaptive)
- *Hibernus* performs adaptive, run-time calibration and management
- Continuous classification of source to select restore policy



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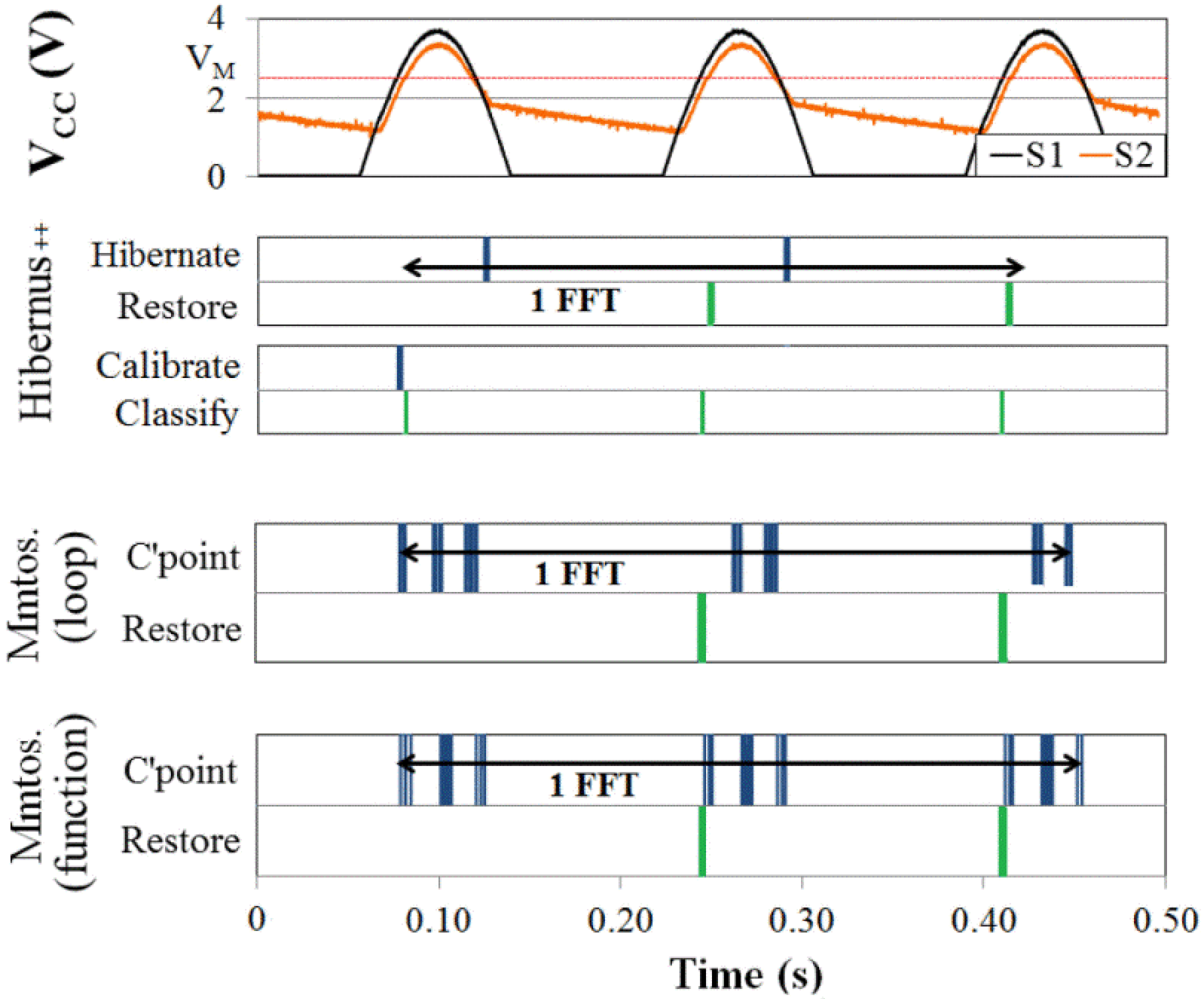
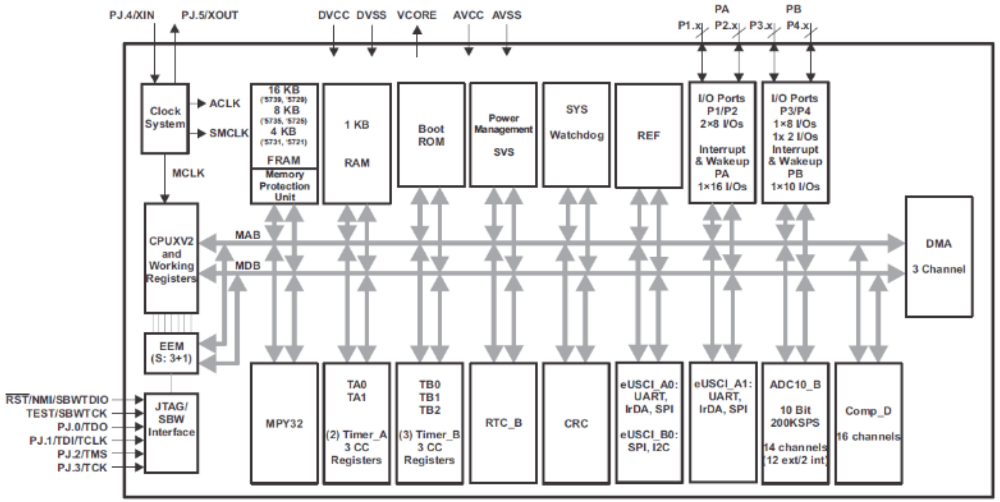
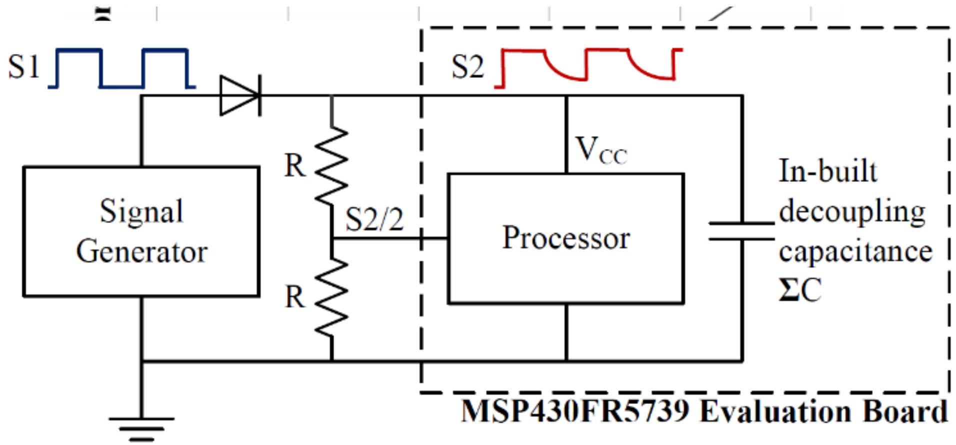


1.3ms to store all Core Registers, General Registers, and 1KB RAM

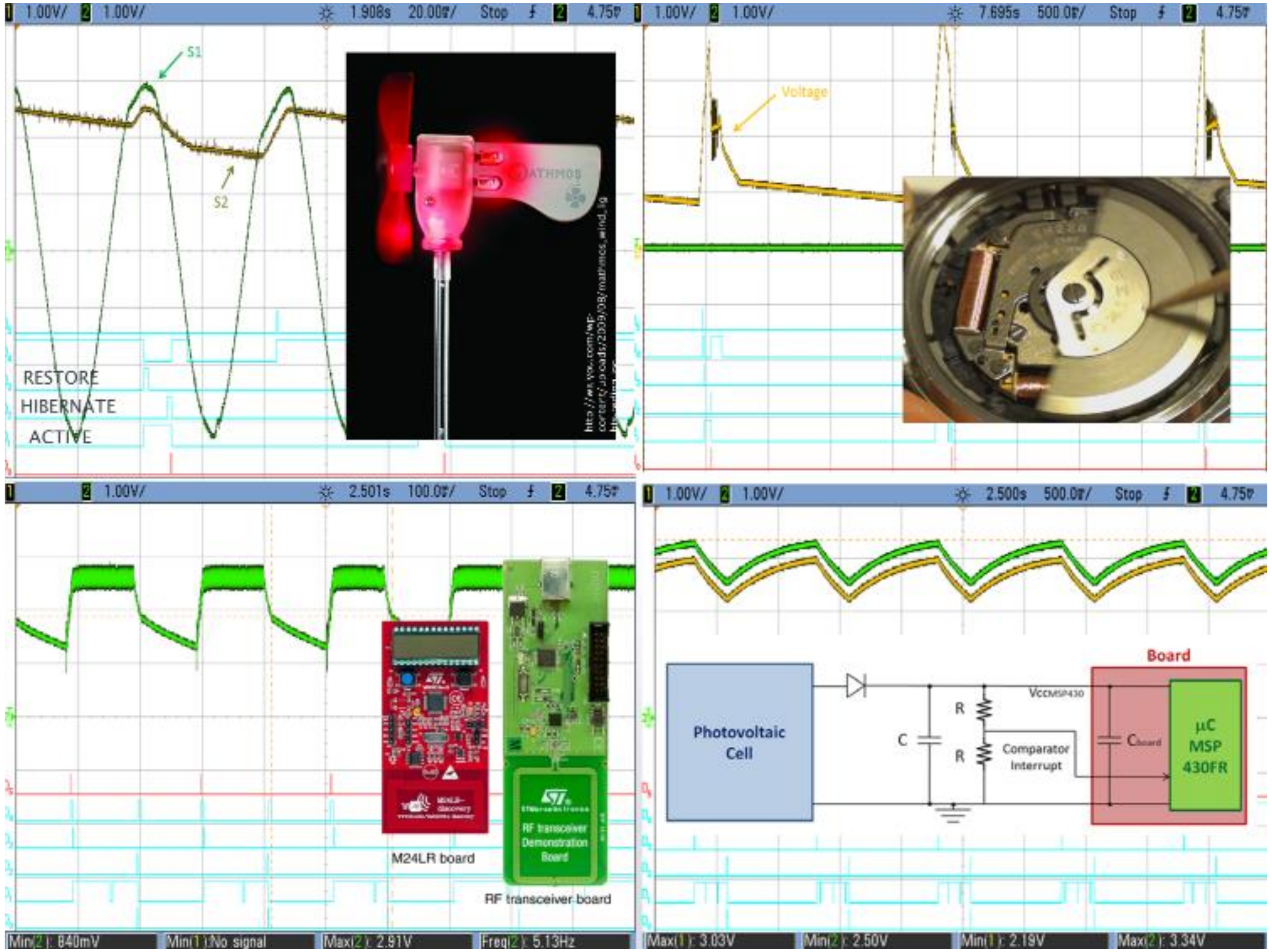




Energy overheads reduced by 50-80%

D. Balsamo, A.S. Weddell, A. Das, A. Rodriguez Arreola, D. Brunelli, B.M. Al-Hashimi, G.V. Merrett, L. Benini, (2016) Hibernus++: a self-calibrating and adaptive system for transiently-powered embedded devices. *IEEE TCAD*, 1-13.
A. Rodriguez, D. Balsamo, A. Das, A.S. Weddell, D. Brunelli, B.M. Al-Hashimi, G.V. Merrett, (2015) Approaches to Transient Computing for Energy Harvesting Systems: A Quantitative Evaluation. In *ENSsys 2015,Korea, 01 Nov 2015*.

Hibernus: Results



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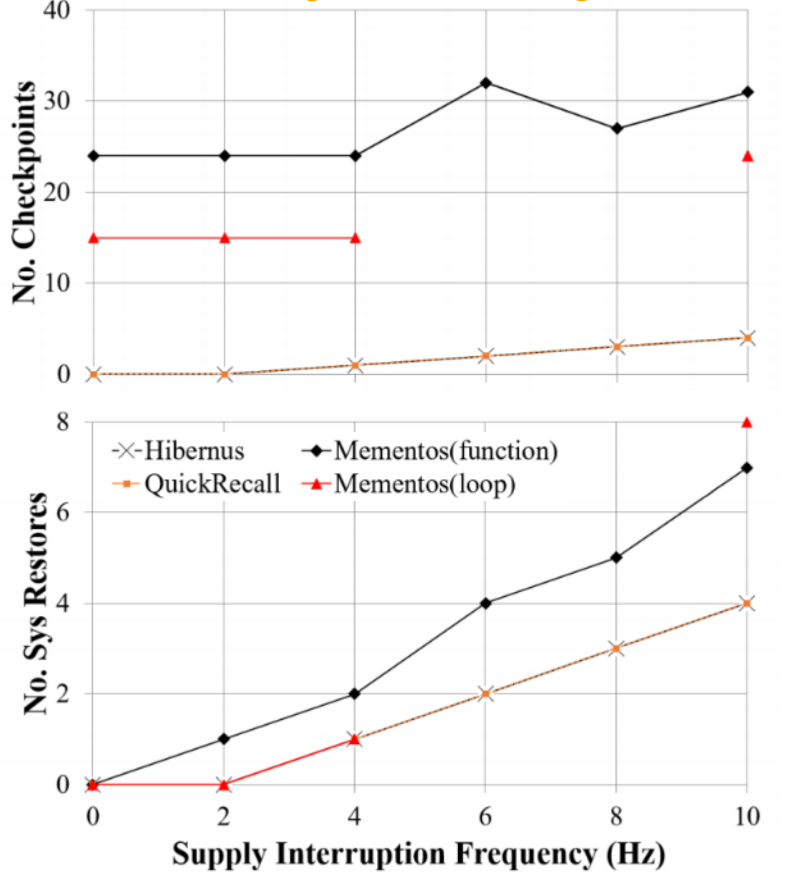

Time overheads reduced by 75-100%
Energy overheads reduced by 50-80%

D. Balsamo, A.S. Weddell, A. Das, A. Rodriguez Arreola, D. Brunelli, B.M. Al-Hashimi, G.V. Merrett, L. Benini, (2016) Hibernus++: a self-calibrating and adaptive system for transiently-powered embedded devices. *IEEE TCAD*, 1-13.
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Hibernus: Results

- Calibrates to the platform to adapt to the available energy storage:

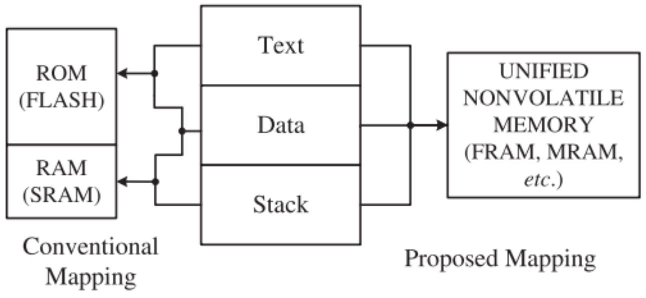
Decoupling capacitance ∑C (µF)	Hibernus			Hibernus++			
	N. Restore	N. Hibern.	Total Time (ms)	N. Restore	N. Hibern.	Total Time (ms)	V_H (V)
10	-	-	-	2	2	395.2	2.03
20	2	2	376.3	2	2	389.4	1.97
30	2	2	376.1	1	1	243.7	1.93
40	2	2	376.0	1	1	238.9	1.91

Using a voltage input of 3V @ 6Hz

  - Where *Hibernus* has been manually calibrated, *Hibernus*++ exhibits a small overhead
  - Where additional energy storage is present, *Hibernus*++ takes advantage of this
  - Where less energy storage is present, *Hibernus*++ adapts to still operate

Hibernus: Results

- QuickRecall: data + program memory is always in NVM
  - A snapshot only transfers registers to NVM
  - Elegant and quicker, but NVM typically consumes greater power

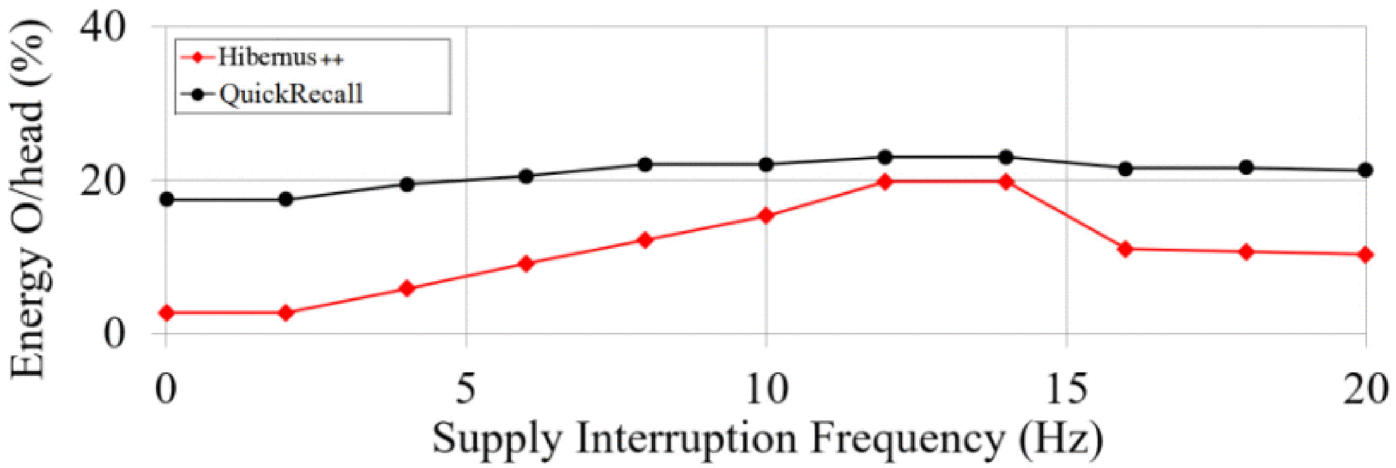


QuickRecall: H. Jayakumar et al. QuickRecall: A HW/SW Approach for Computing across Power Cycles in Transiently Powered Computers. *J. Emerg. Technol. Comput. Syst.* 12, 1, Article 8 (Aug 2015).

$$E_{hibernus} = \eta_\alpha E_\alpha + \eta_\beta E_\beta$$

$$E_{QuickRecall} = \eta_\alpha E_\alpha$$

$$f_{crossover} = \frac{P_{FRAM} - P_{SRAM}}{E_{hibernus} - E_{QuickRecall}}$$



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Power-Neutral Computing

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- In Energy-Neutral computing, $\int_{(n-1)\cdot T}^{n\cdot T} P_h(t)dt = \int_{(n-1)\cdot T}^{n\cdot T} P_c(t)dt$ over a 'large' *T*
- In Power-Neutral computing, $P_h(t) = P_c(t)$ (*or as close as is possible*)
- Modulate the power consumption using DPM 'knobs', e.g.:
  - Clock frequency
  - Core voltage and clock frequency
  - Power gating processor elements
  - Mapping execution to different combinations of processing elements
  - … etc

Power-Neutral Computing

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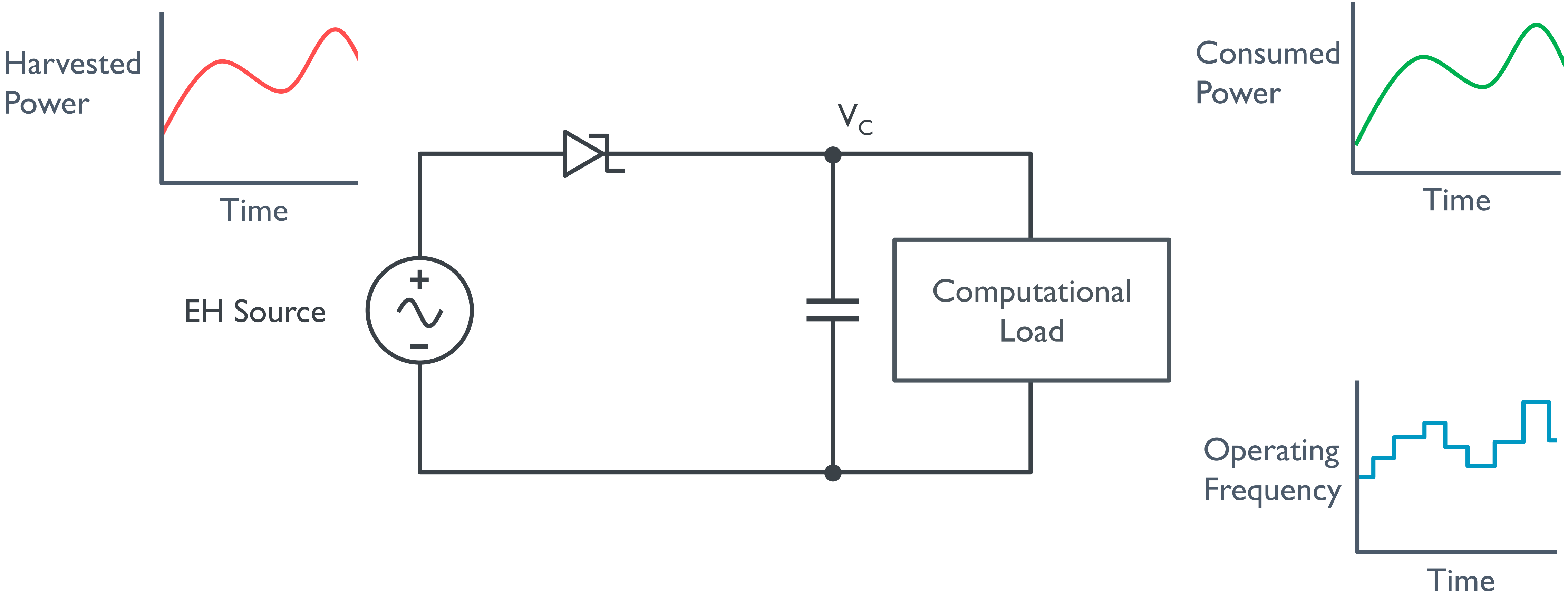
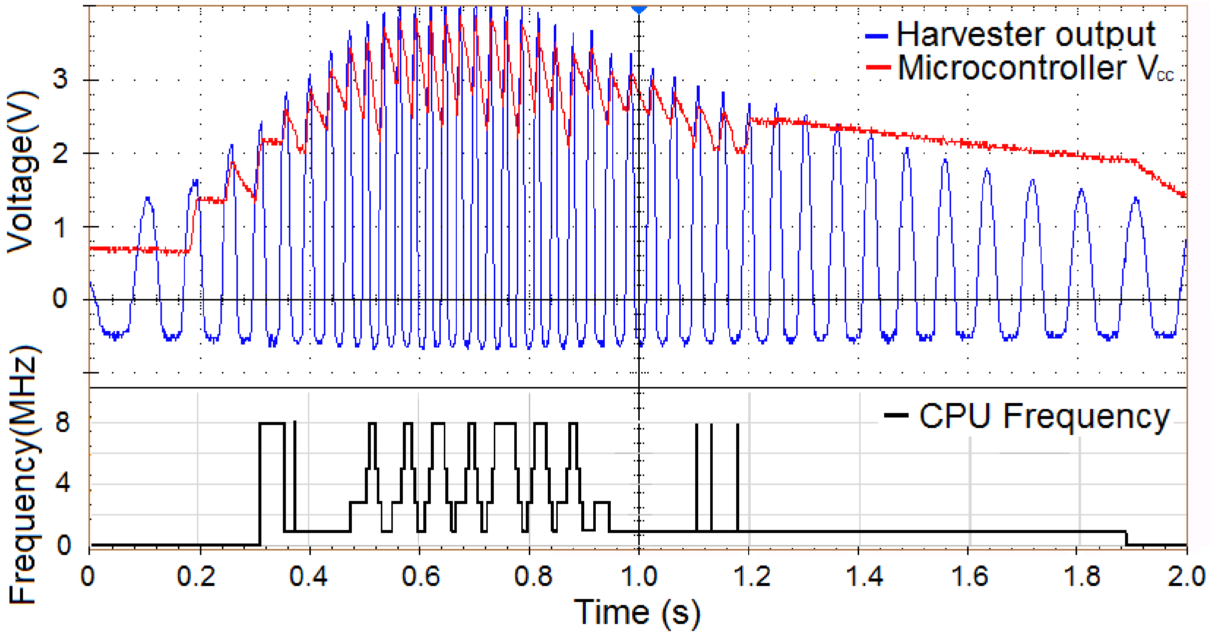
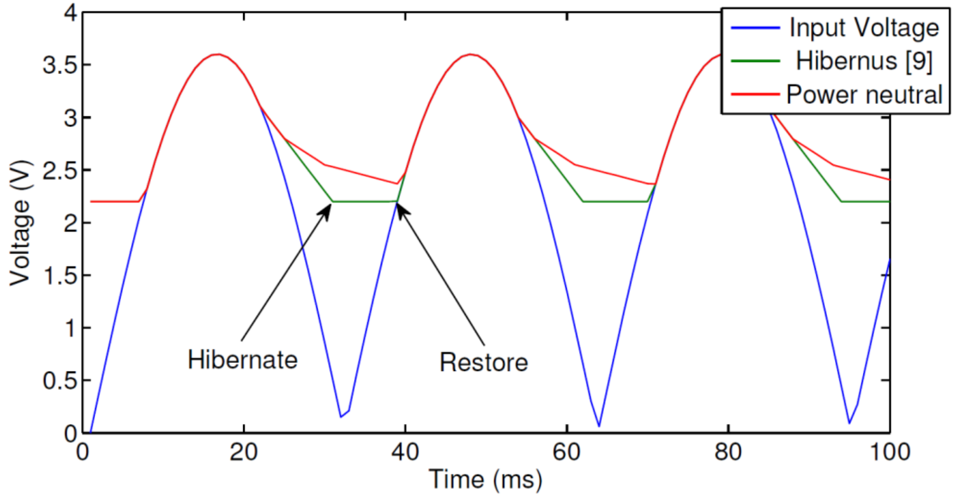


Fletcher, Benjamin J., Balsamo, Domenico and Merrett, Geoff V. (2017) Power neutral performance scaling for energy harvesting MP-SoCs At DATE 2017, Lausanne.

Power-Neutral Computing

- On our embedded platform, power-neutrality significantly reduced *Hibernus* overheads





D. Balsamo, A. Das, A.S. Weddell, D. Brunelli, B.M. Al-Hashimi, G.V. Merrett, L. Benini, (2016) Graceful Performance Modulation for Power-Neutral Transient Computing Systems. *IEEE Trans. Computer-Aided Design of Integrated Circuits and Systems*

Power-Neutral Computing

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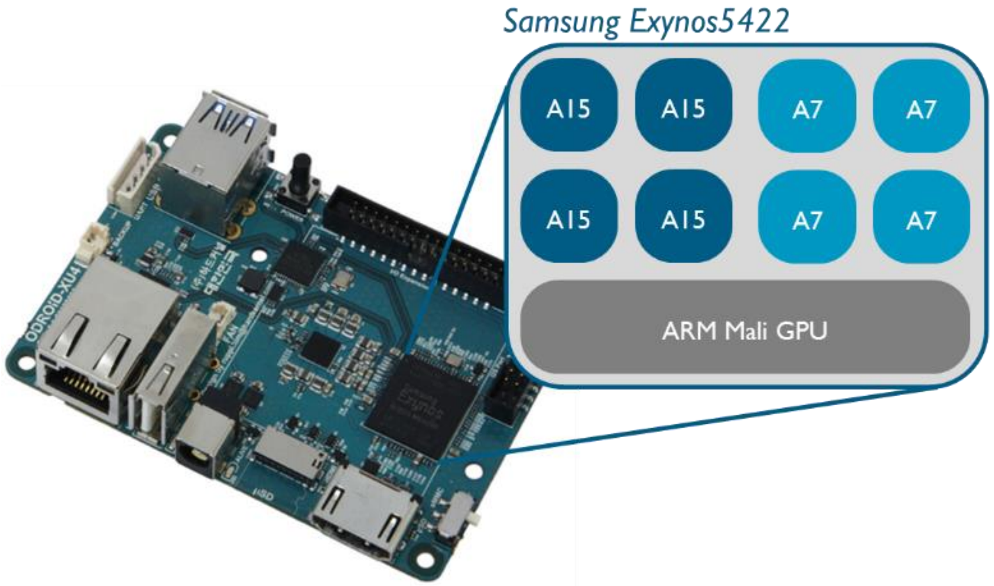
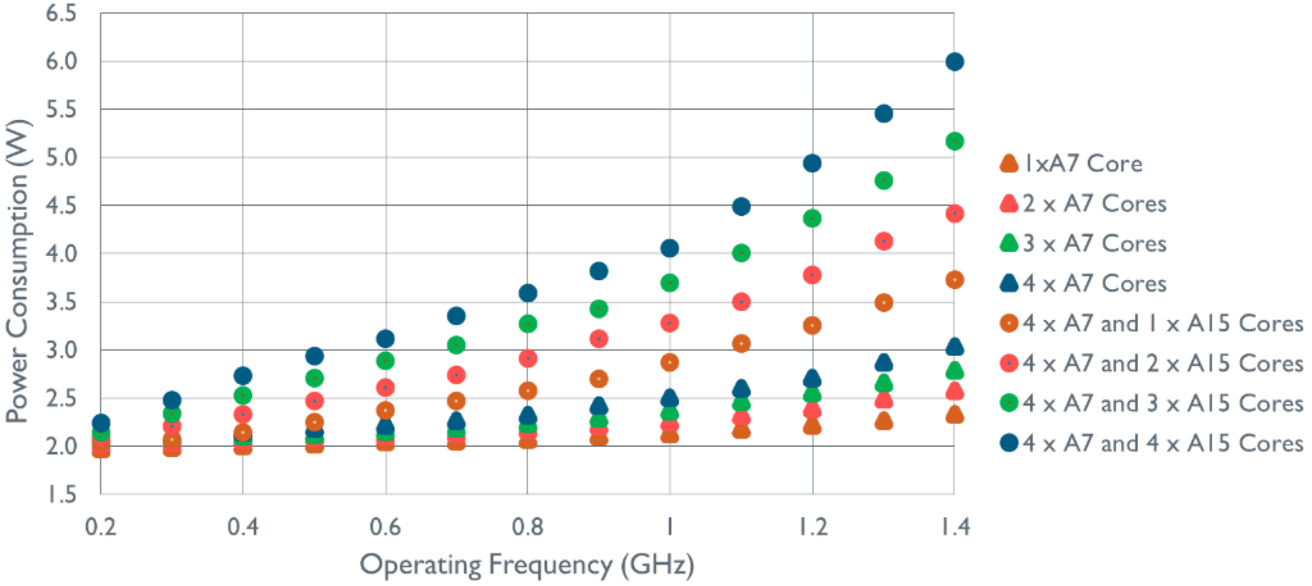
- Applied to the ODROID XU-4 MPSoC powered by a 1340cm^2 Photovoltaic Array





- System successfully operated for many hours during daylight

Fletcher, Benjamin J., Balsamo, Domenico and Merrett, Geoff V. (2017) Power neutral performance scaling for energy harvesting MP-SoCs At DATE 2017, Lausanne.

Power-Neutral Computing

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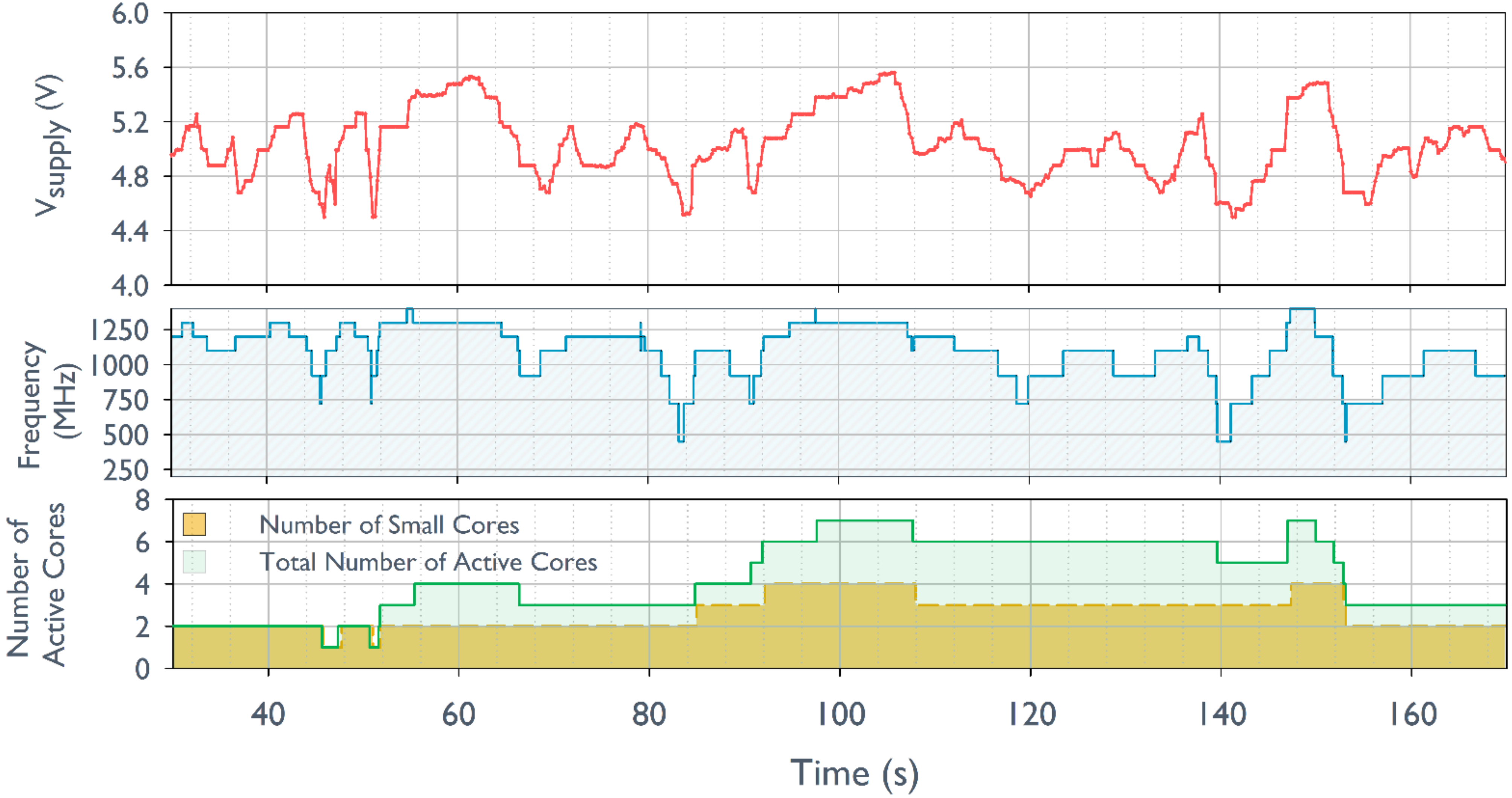

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Conclusions: Energy-Driven Computing

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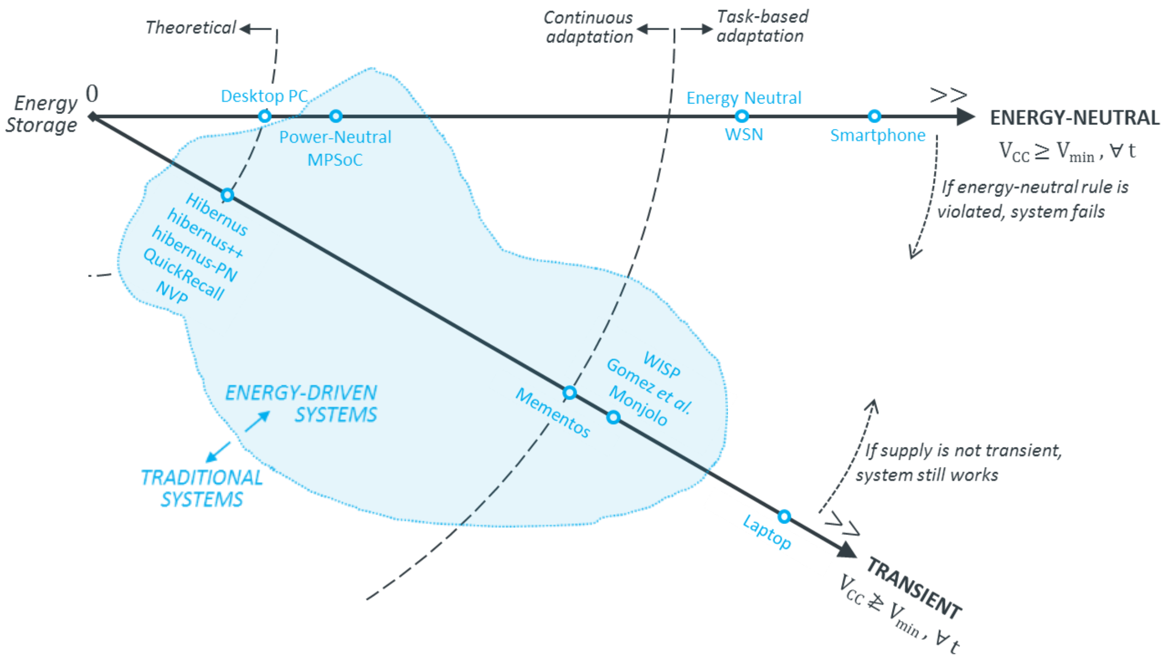
- Energy harvesting and *energy-neutral* systems often add significant complexity to become 'battery-like'
- Taking an *energy-driven* approach to design gives consideration to the energy source and its dynamics as an integral part in the design process.
- *Transient* computing (computation only when power is available) and *power-neutral* computing (adapting computation to available power) can be used in *energy-driven* systems.
- However, many significant challenges still remain!



Questions?

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