From Playing with Constraints…
… to Thinking in Terms of Limits
Towards New Research Directions in CS

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And a lot of colleagues on Twitter...
**Abstract**

The future of computing research relies on addressing an array of limitations on a planetary scale.

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1 https://dl.acm.org/doi/10.1145/3183582
Where I Stand, and Personal Motivations

Questioning Sustainability of Digital Systems

Tentative Definition of a (new) Research Direction

This is Not a Conclusion
Why this Introduction?

Because no research is neutral. It’s better to explain where we stand, first, so that the audience can decide by themselves how to interpret what we say.
Better Said by Howard Zinn:

This is not going to be a neutral class, I said. I don’t believe in neutrality. I believe neutrality is impossible, because the world is already moving in certain directions. Wars are going on. Children are starving. And to be neutral, to pretend to neutrality, to not take a stand in a situation like that is to collaborate with whatever is going on, to allow it to happen. I did not want to be a collaborator with what was happening. I wanted to enter into history. I wanted to play a role. I wanted my students to play a role. I wanted us to intercede. I wanted my history to intercede and to take a stand on behalf of peace, on behalf of a racial equality or sexual equality, and so I wanted my students to know that right from the beginning, know you can’t be neutral on a moving train.\(^2\)

\(^2\).http://firstrunfeatures.com/zinn.html
About Me: 30 Years Playing with Constraints...

- 30 years of research and teaching on (mainly critical and hard real-time) embedded systems; HW/SW interface, safety properties, high-level languages, model-driven approaches, virtual prototyping, constrained systems (time, memory, ...), long-term development, dealing with certification authorities, ...

- A domain where “try-a-bigger-machine” is not an option but there’s no need to be faster than the music!

- Collaborations with Airbus, STMicroelectronics, OrangeLabs, ...

- Application domains: avionics, railways, consumer electronics, sensor networks and smart cities, ...
... Towards Thinking in Terms of Limits

1) **Local** constraints are not enough, we need to think in terms of **global** limits

2) We should explore other futures, **just in case**...
   - Green growth does not exist (see\(^3\))
   - Sustainable development does not exist
   - Tech alone *cannot* save us

3) My concern with the environmental impacts of digital technologies meets other concerns:
   Fragility, global surveillance, biaises in AI, lethal autonomous weapons, other questionable (and sometimes even definitely bad) uses ...

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Broadening my Research Environment

- An early participant in Campus d’Après Grenoble⁴
- A teacher confronted with students (and colleagues) asking: “what will we do in 2030?” and a member of Make Ensimag Green Again
- A researcher facing the huge amount of money spent on one future only: the endless growth of technical systems, and the idea that (only) tech can/will save us.
- One of the initiators of the very young transdisciplinary seminar on the Anthropocene in Grenoble

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⁴https://campusdapres-grenoble.org/
This Talk

1. Where I Stand, and Personal Motivations

2. Questioning Sustainability of Digital Systems
   - Several Sources of Fragility
   - Environmental Impacts of Digital Technologies

3. Tentative Definition of a (new) Research Direction
   - Why and How?
   - From Playing with Constraints...
     - Example 1: Consumer Electronics
     - Example 2: Control SW in the Avionics Domain
     - Lessons Learnt
   - ... To Thinking in Terms of Limits
   - Providing Grounds for Teaching
   - Providing Expertise for Citizens and Bases for Informed Choices

4. This is Not a Conclusion
1. Where I Stand, and Personal Motivations

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Questioning Sustainability of Digital Systems

- Several Sources of Fragility
- Environmental Impacts of Digital Technologies
Security, Safety, Privacy, Loss of Expertise, Obsolescence, HW Manufacturers, Democratic Choices... (1)

- Data Breaches 2019 - 2021
- Contact-Tracing Tech and the Chock Doctrine
- Boeing 737Max
- AWS outage impacts thousands of online services
- Spectre and Meltdown family of “bugs”, Intel vulnerabilities

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8 https://www.zdnet.com/google-amp/article/aws-outage-impacts-thousands-of-online-services/
9 https://www.theregister.com/AMP/2021/06/09/intels_latest_patch_set/
Security, Safety, Privacy, Loss of Expertise, Obsolescence, HW Manufacturers, Democratic Choices… (2)

- Ransomware (fueled by crypto-currencies?)
- Orange, emergency services\(^{10}\)
- Cobol Software never Dies (Loss of Expertise)
- Flash no longer maintained, trains in China (obsolescence)
- 2021 severe drought in Taiwan, TSMC problems\(^{11}\)
- The Case of 5G Deployment (Democratic choices, bad arguments, … )

\(^{10}\) https://www.lemonde.fr/economie/article/2021/06/04/orange-dans-la-tourmente-apres-la-panne-des-numeros-d-urgence_6082787_3234.html
\(^{11}\) https://blogs.mediapart.fr/geographies-en-mouvement/blog/300521/lindustrie-mondiale-bientot-sec
The World Relies on One Chip Maker in Taiwan, Leaving Everyone Vulnerable

Taiwan Semiconductor Manufacturing Co.’s dominance poses risks to the global economy, amid geopolitical tensions and a major chip shortage.

A GPS Outage Would Cost 1 Billion per Day

Study finds that a GPS outage would cost $1 billion per day

90 percent of the technology's financial impact has come since just 2010.

ERIC BERGER - 6/14/2019, 6:38 PM

https://arstechnica.com/science/2019/06/study-finds-that-a-gps-outage-would-cost-1-billion-per-day/
Related Questions

- How to avoid the intrinsic fragility of systems that are: two complex, two quickly developed, for too short-term life cycles, based on a too-concentrated HW industry or a Centralized Architecture?
- How to design simpler, more understandable systems, less interconnected, built to last?
- How to guarantee a constant flow of people and groups able to understand a digital system as a whole?
- How to allow for democratic choices in technological developments?
Questioning Sustainability of Digital Systems

- Several Sources of Fragility
- Environmental Impacts of Digital Technologies
How to Estimate the Impact? Questioning Optimizations

Approaches and sources? Ecoinfo CNRS

Two important aspects (among others):
- Don’t forget the impact of the manufacturing phase when optimizing the use phase
- Optimizations often lead to massive rebound effects

Let us look at one example...

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14 https://ecoinfo.cnrs.fr/
Questioning Sustainability of Digital Systems

Environmental Impacts of Digital Technologies

Typical Situation in 2005

2005
Typical Situation in 2020
Mobile Communications 2005 - 2020

2005: Use them to place and receive calls “everywhere”; charge once a week; telephone booths remain; around 140 submarine communications cables\(^\text{16}\): each capable of carrying 3,2 Tbits/s

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\(^{16}\) See [https://cablemap.info/default.aspx](https://cablemap.info/default.aspx) or [https://en.wikipedia.org/wiki/Submarine_communications_cable](https://en.wikipedia.org/wiki/Submarine_communications_cable)
Mobile Communications 2005 - 2020

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- 2005 ... 2020: Huge improvements of the devices (hardware, software, batteries, screens, casing, ...) + huge improvements of the infrastructure

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- 2005 ... 2020: Huge improvements of the devices (hardware, software, batteries, screens, casing, ...) + huge improvements of the infrastructure

- 2020: Use them mainly as portable always-connected computers; have allowed new services (Uber, maps+GPS, ...); charge twice-a-day or carry an external battery; telephone booths have disappeared; electric charging stations have appeared everywhere (bicycle-powered in railway stations, cafes, ...) there are now around 400 cables, each capable of carrying: 320 Tbit/s

\(^{16}\) See https://cablemap.info/default.aspx or https://en.wikipedia.org/wiki/Submarine_communications_cable
What Happened? Evolution of the Global Impact of such Mobile Devices and the Underlying Infrastructure?

Both the potential uses and the environmental impacts increased a lot.

Is it ok? Do smartphones replace (or rather add up to) something else that also has a very bad impact (laptops, cameras, ...)? How to decide whether optimizations win over rebound effects?

These cannot be “tech-only” questions and answers.
Agriculture/Drinking Water or Data Centers?

Drought-stricken communities push back against data centers

As cash-strapped cities welcome Big Tech to build hundreds of million-dollar data centers in their backyards, critics question the environmental cost.

Theoretically Thinkable Paths

Charge once a week

HUGE improvements in battery + hw, sw ...

Charge twice a day

Many more functions

SAME functions charge once a month (?)

Charge once a week

More functions
1 Where I Stand, and Personal Motivations

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4 This is Not a Conclusion
Tentative Definition of a (new) Research Direction

Why and How?

From Playing with Constraints...

... To Thinking in Terms of Limits

Providing Grounds for Teaching

Providing Expertise for Citizens and Bases for Informed Choices
Several Paths...

Current State

Slippery slope

Limit

Smaller impact

Same impact

Much greater impact

Many more functions

Endless growth?
On the Need for a Better Research Coverage

Ensure not all research is devoted to the slippery slope.

Divert some energy and thoughts (hopefully money) to other paths...

Just in case...
Tentative Definition of a (new) Research Direction

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Tentative Definition of a (new) Research Direction

Why and How?

From Playing with Constraints...
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Providing Grounds for Teaching

Providing Expertise for Citizens and Bases for Informed Choices
Some Characteristics of the Domain

- Very strong time-2-market constraints
- Tyranny of the “new”, “innovation” is more valued than maintenance
- Technically:
  - Communication between HW and SW designers needed more than ever because the HW keeps changing (hence the advent of concurrent engineering approaches like TLM, …)
  - Aggressive optimizations for power consumption introduce “new” sources of bugs (aka “energy bugs”, e.g., lock/unlock problems, battery drain but also functional problems)
**HW Optimizations**

- **Clock Gating** (turn off the clock): $P_{\text{dynamic}} = 0$, but $P_{\text{static}}$ unchanged

- **Dynamic Voltage and Frequency Scaling (DVFS)** reduce $V$, and then $F$. A circuit can have a (small) number of operating points $(V, F)$. Switching between them has a cost and takes time.

- **Power Gating** (switch a component on/off); Switching is very costly (save/restore state); application-level information is needed (e.g., GPS is not longer used, switch the sub-circuit off).
Characterizing and Detecting Energy Bugs

Wakelocks and other stories, a few references:

- Unit Testing of Energy Consumption of Software Libraries\(^{18}\)
- Detecting Energy Bugs in Android Apps Using Static Analysis\(^{19}\)
- Categorization and Detection of Energy Bugs and Application Tail Energy Bugs in Smartphones\(^{20}\)

\(^{18}\) https://hal.archives-ouvertes.fr/hal-00912613
\(^{19}\) https://link.springer.com/chapter/10.1007/978-3-319-68690-12
\(^{20}\) https://uwspace.uwaterloo.ca/bitstream/handle/10012/10862/abbasi_abdul.pdf
Concurrent Engineering: Transaction-Level Modeling (TLM)\textsuperscript{21}

Precise Simulation Models with Temperature Models and Actual Embedded Code
Precise Simulation Models with Temperature Models and Actual Embedded Code

```c
if (T > thr) { switch "other" off; turn CPU to (V1,F1) }
```

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**Temperature model**

**Floorplan Bus**

- CPU
- MEM
- other
- mem
- BUS
- temp

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F. Maraninchi (Verimag/Ensimag)
Precise Simulation Models with Temperature Models and Actual Embedded Code

if (T > thr) { switch "other" off; turn CPU to (V1,F1) }

Power domains V, F for each block
Precise Simulation Models with Temperature Models and Actual Embedded Code

if (T > thr) { switch "other" off; turn CPU to (V1,F1) }

Power densities

Power domains V, F for each block

Temperature model

Embedded code
Precise Simulation Models with Temperature Models and Actual Embedded Code

```plaintext
if (T > thr) { switch "other" off; turn CPU to (V1,F1) }
```

Power domains $V, F$ for each block

Temperature model

Floorplan

Bus

CPU

MEM
Precise Simulation Models with Temperature Models and Actual Embedded Code

\[
\text{if } (T > \text{thr}) \{ \text{switch "other" off; turn CPU to (V1,F1)} \}
\]
Precise Simulation Models with Temperature Models and Actual Embedded Code

if (T > thr) { switch "other" off; turn CPU to (V1,F1) }

P=f(traffic) may take contention into account; the Joule–per–bit model cannot.

Power densities

Temperature model

Floorplan

Bus

CPU

MEM

Power domains
V, F for each block

P=f(traffic) may take contention into account; the Joule–per–bit model cannot.
Example Simulation Results

22 Temperature models with https://team.inria.fr/alf/software/atmi/
Where Could Limits Come From?

- Chip shortage?
- Intermittent Electricity?
- Economic choices (no unlimited packages)?
- Regulations?
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Some Characteristics of the Domain

- Hard real-time, WCET problem on modern HW
- Scarce resources (time, memory, heat, ...)
- Long life (obsolescence problem with HW platforms and OSes or compilers)
- Embedded: monitor-and-repair is not an option
- Flying: when an error occurs, no easy fail-safe behavior (contrary to trains)
- Certification authorities require predictability (through determinism)
- DSLs, no Dynamic Memory Allocations, Static Scheduling (no OS) approaches
Reactivity to an Environment, Real-Time Programs

A typical real-time program:

initializations
while (true) {
    --- point (1)
    get inputs
        (read sensors)
    compute outputs
        and update memory
    write outputs
        on the actuators
    --- point (2)
}

The time it takes to execute the code between points (1) and (2) is the time between two samples of the inputs. This is real time.

The outputs to the environment may have some influence on future inputs. This is reactivity.
The WCET Estimation Problem and
The Need for More Deterministic Processors

- Static (beforehand) estimation is needed (no fail-safe behavior that could be used if problems are detected during the flight)
- It was easy with “old” processors like the simple 1990’s processors (e.g., Motorola 68000 family)
- But they are no longer available and...
- Need for more computing power and less energy consumption?
- What about multi- and many-core processors in the critical domain?\(^\text{24}\)

\(^{24}\) https://www-verimag.imag.fr/CAPACITES.html
Static Conservative (Approximate) Functional Validation, Over-provisioning

- Critical $\Rightarrow$ (formal) validation
- Critical $+$ no fail-safe behaviour $\Rightarrow$ static validation
- Complex $+$ required static validation $\Rightarrow$ approximate validation
- Approximate validation $\Rightarrow$ Over-provisioning
- More complex HW $+$ SW $+$ OS $\Rightarrow$ even harder validation

Is there a fix-point?
Limits?

Staying Within the Limits of Predictable Systems:

- Do not use a general-purpose programming language
  A DSL can add a few things to a general-purpose language, but can be used to remove something from a GP language. Example: the total amount of needed memory should be statically computable.

- Do not use general-purpose OSes, but RTOSes

Designing for 30+ years
Certification authorities introduce some friction
Technical Details on a DSL that Limits Memory Uses

See Lustre\textsuperscript{25}

In a general-purpose programming language (Java), it may be quite difficult to compute the maximum amount of memory needed for any possible execution.

In a DSL it’s hard-wired. Some behaviors cannot be programmed. And it’s good news!

\textsuperscript{25}https://www-verimag.imag.fr/lustre-v6.html
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Don’t Forget the HW

Building SW with constraints (e.g., timing predictability) if the HW is not built for that is a nightmare; a stack of very clever HW and SW layers that are meant to make your good against your own will is indistinguishable from magic.
Don’t Forget the HW

- Building SW with constraints (e.g., timing predictability) if the HW is not built for that is a nightmare; a stack of very clever HW and SW layers that are meant to make your good against your own will is indistinguishable from magic.
- Optimizing a device enables packing more functions within the same energy budget, but:
  - If the HW is too complex, then the SW will not be able to exploit it fully; less “optimized” (or sophisticated) may actually lead to more efficient HW+SW systems!
Tentative Definition of a (new) Research Direction

From Playing with Constraints...

Tomorrow will be Better... ?

- Always hoping for more efficient devices tomorrow implies a lot of waste
- It’s become hard to teach all the details in a computer science curriculum.
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Limits, Computing with Limits

- Giorgios Kallis, *Limits, Why Malthus Was Wrong and Why Environmentalists Should Care*\(^{26}\)
- LIMITS series of workshops\(^ {27}\), Motto: *prepare a future of scarcity, in a world of abundant resources*
- Article “Computing Within Limits” \(^ {28}\)
- Related approaches: *collapse informatics* (see above paper)

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\(^{26}\) [https://www.sup.org/books/title/?id=29999](https://www.sup.org/books/title/?id=29999)

\(^{27}\) [https://computingwithinlimits.org/2021/](https://computingwithinlimits.org/2021/)

\(^{28}\) [https://dl.acm.org/doi/10.1145/3183582](https://dl.acm.org/doi/10.1145/3183582)
How to Avoid the Slippery Slope?

- Current State

- Slippery slope

- Smaller impact

- Same impact

- Much greater impact

- Many more functions

- Endless growth?
Existing Example (1980’s - now)

+ single-loop code

Dedicated Architectures
- PRET Machine (Berkeley...)
- Kalray chip
- ...

+ Dedicated languages
+ Dedicated SW Eng. Tools
+ Dedicated "social acceptance" framework

LIMITS FOR PREDICTABILITY

Ordinary SW on Ordinary HW

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29 Par © Raimond Spekking / CC BY-SA 4.0 (via Wikimedia Commons), CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=106304210
Limits for Digital Systems?

Technical approach — for people coming from already-constrained (and somewhat limited) contexts:

- De-Construct to Identify anti-limits (= intrinsically unbounded contexts)
- Rebuild from scratch as a thought-experiment (to escape the tyranny of the state of affairs), self-impose limits on the way

Not only technical:

- Decide beforehand what to do with the gains of optimized systems
- Think in terms of priorities and choices (but avoid moral judgements)
There are anti-limits if a digital system...

- Requires an increasing amount of resources globally (bitcoin alone, or with other crypto-currencies, Chia$^{30}$, PKT$^{31}$, etc.)

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$^{30}$[https://en.wikipedia.org/wiki/Chia_(cryptocurrency)]

$^{31}$[https://pkt.cash/]
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- Assumes unlimited storage (initial advertisement of gmail)

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- Assumes (HW+SW+vendor cloud) availability with no time limit (home automation)
- (Needs 24/7 connectivity and cloud access) $\times$ (growing number of users) (instead of sharing)
- Built to allow for “unlimited” functional extensions (web)

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- Deployment is profitable only if there are more users and/or more usage (5G)

\(^{30}\) https://en.wikipedia.org/wiki/Chia_(cryptocurrency)  
\(^{31}\) https://pkt.cash/
Candidate Limits (and Induced Constraints)

- Gemini (heavier than gopher, lighter than the web, ...)\textsuperscript{32} - same idea as restricted DSLs, no images, no extensions, ...
- All configurations in:
  \{ intermittent, quotas \} \times \{ power, connection, memory, computing power \}
- no centralized architecture, no cloud, no network, no immediate service delivery
- Carefully chosen DSLs (no dynamic allocation, ...) everywhere
- The Ultimate Limit: What if we Stopped Manufacturing New HW Now? See also “collapse informatics”, e.g., CollapseOS\textsuperscript{33}

\textsuperscript{32}https://gemini.circumlunar.space/
\textsuperscript{33}https://collapseos.org/
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Back to Basics

Define small sufficient knowledge
Don’t forget the big picture
Responsible SW is sometimes no software (e.g., electronic voting)
Responsibilities of SW professionals, ethics-by-design, oaths\(^{34}\), ...
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If we have to choose, what do we keep?, How do We Share?

Wikipedia or real time face recognition for border security (or connected shoes)? And the cost of AI behind it? Not only constraints and optimization.
Anatomy of AI (Amazon echo)

https://anatomyof.ai/
Surgeon in London are performing remote operation on a banana in California using 5G

With the advent of 5G, new possibilities are coming for orthopedic surgery. The Low latency of 5G is the main enabler here. As we know Latency occurs when data is sent across a network, either using cables or through wireless connectivity with cell towers, to a device or machine. The higher the latency, the longer those messages take to send. By lowering the latency to near instantaneous, 5G is opening up a whole of new possibilities for Surgery Industry, enabling surgeons to perform remote surgery from remote locations, thousands of miles away.

https://www.5gworldpro.com/blog/2021/02/01/surgeon-in-london-performs-remote-operation-on-a-banana/
Submarine communication cables (2018)

https://www.submarinecablemap.com/
À Angers, 50 000 capteurs et 178 millions d'euros pour la smart city

Angers Loire Métropole a noué on contrat sur douze ans avec un consortium mené par Engie. Objectifs : économiser 101 millions d'euros sur 25 ans et développer de nouveaux services.

*Mis à jour le 20/11/19 16:54*
1. Where I Stand, and Personal Motivations

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4. This is Not a Conclusion
Let us Think of Alternate Futures

– Improving existing digital systems is ok (but don’t forget rebound effects)
– Start thinking in terms of limits, just in case...
– Be prepared to trade convenience for a guarantee on the absence of anti-limits

And remember: you can’t be neutral on a moving train.
Questioning endless growth is not neo-luddism; it is our responsibility of professionals.
The End. Thank you.
Questions ?