CHAIR FOR COMPILER CONSTRUCTION

cfaed CENTER FOR ADVANCING ELECTRONICS DRESDEN

Parallel programming: Current and future systems

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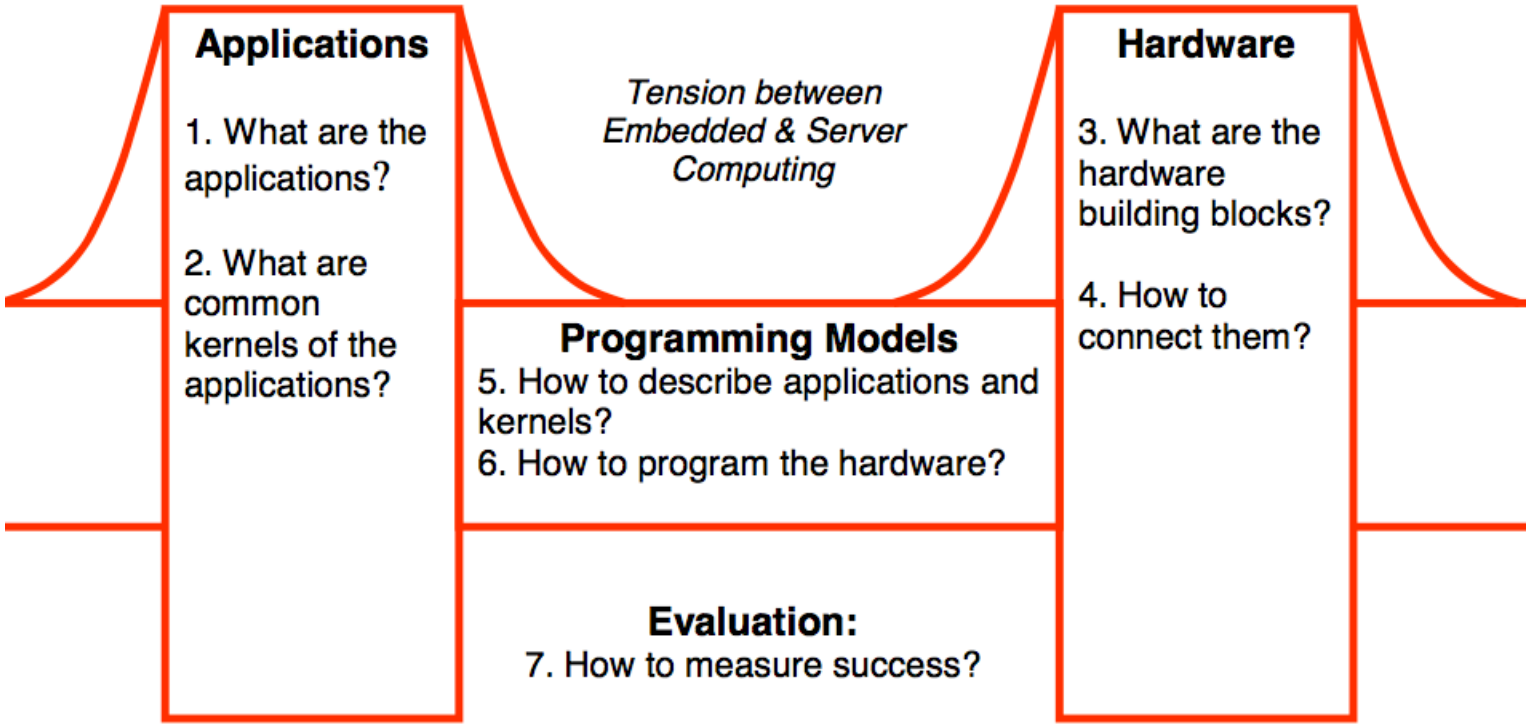
50-year Celebration: Department of Electronics, Universidad de Antioquia
IEEE Colombian Conference on Communications and Computing (COLCOM)
Medellin, Colombia, May 16 2018

Programming models



Asanovic, K.; Bodik, R.; Catanzaro, B. C.; Gebis, J. J.; Husbands, P.; Keutzer, K.; Patterson, D. A.; Plishker, W. L.; Shalf, J.; Williams, S. W. & Yelick, K. A. The Landscape of Parallel Computing Research: A View from Berkeley. EECS Department, University of California, Berkeley, 2006

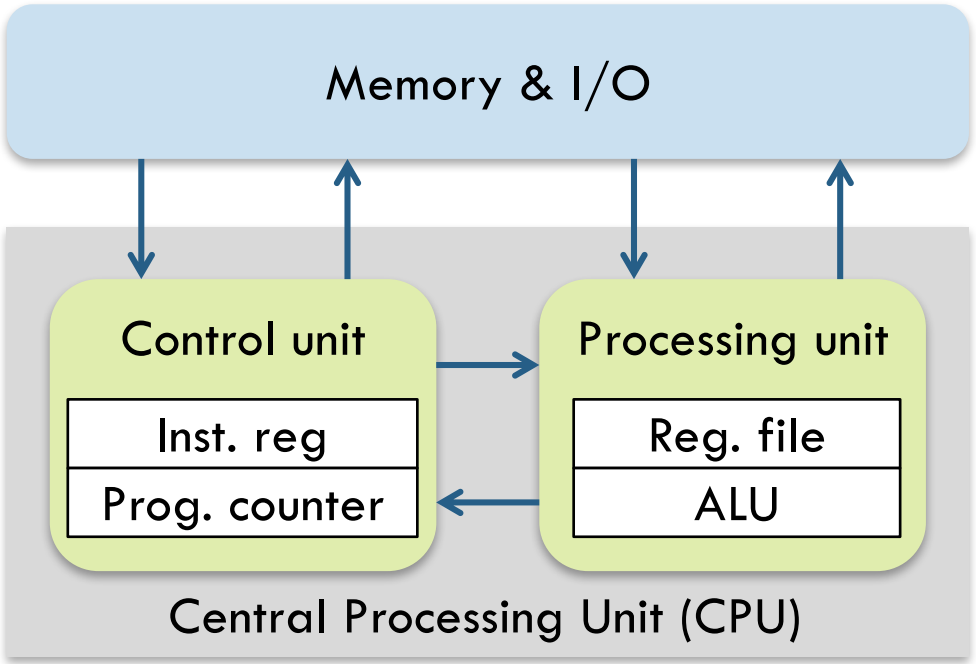
Von Neumann and Sequential Programming

- Program: sequence of instructions in memory

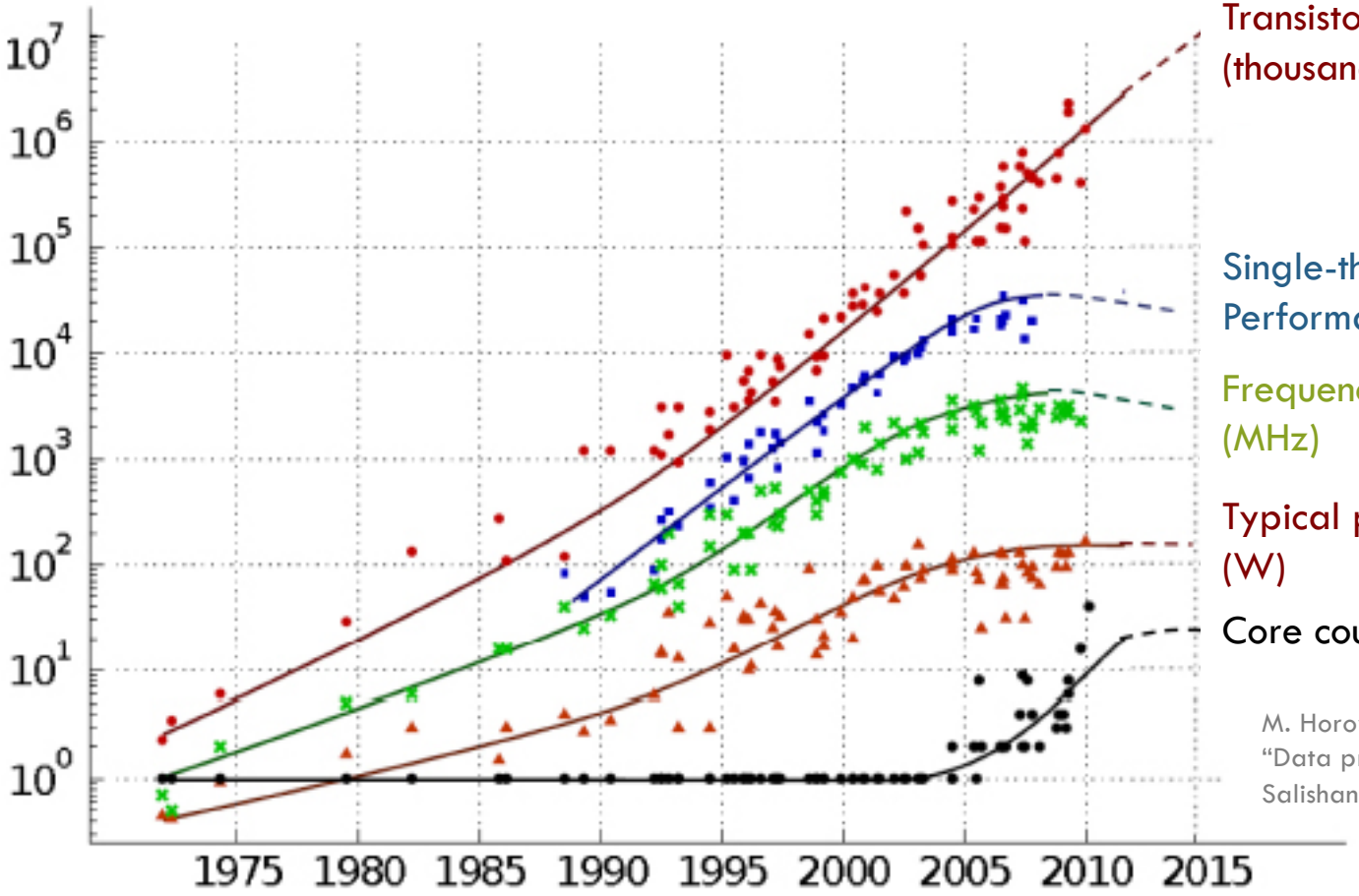
```
double t7[12];
for (unsigned i7 = 0; i7 < 3; i7++) {
  for (unsigned i6 = 0; i6 < 2; i6++) {
    for (unsigned i5 = 0; i5 < 2; i5++) {
      t7[(i5 + 2*(i6 + 2*(i7)))] = 0.0;
      for (unsigned i8_contr = 0; i8_contr < 3; i8_contr++) {
        t7[(i5 + 2*(i6 + 2*(i7)))] += A[(i5 + 2*(i8_contr))]
            * t6[(i6 + 2*(i7 + 3*(i8_contr)))];
      }
    }
  }
}
double t8[1];
double t9[1];
for (unsigned i11 = 0; i11 < 2; i11++) {
  for (unsigned i10 = 0; i10 < 2; i10++) {
    for (unsig  i9 = 0; i9 < 2; i9++) {
      t9[0] = 0.
      for (unsigne                - 0; i12_contr < 3; i12_contr++
          )
        t9
      }
      t8[
      doub
      t10
      v[(
    }
  }
}
```

Good abstractions:

- "High-level" languages (C, …)
- Efficient HW implementation



Why parallel programing?



Transistors (thousands)

Single-thread Performance

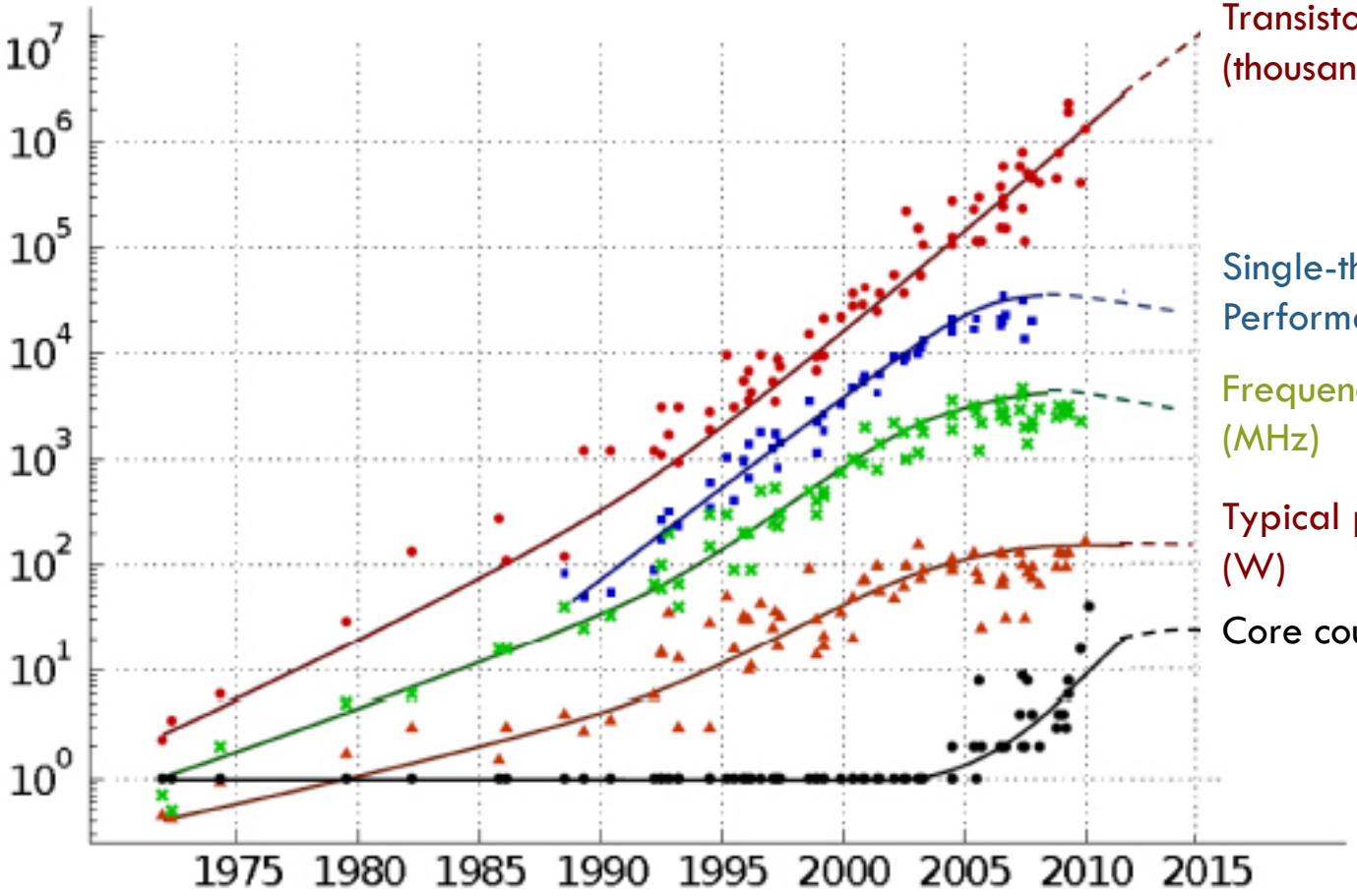
Frequency (MHz)

Typical power (W)

Core count

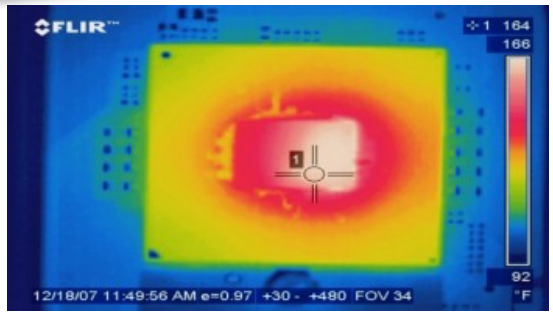
M. Horowitz, F. Labonte, et al. Dotted-line by C. Moore, "Data processing in exascale-class computer systems," The Salishan Conference on High Speed Computing, 2011

Why parallel programing?



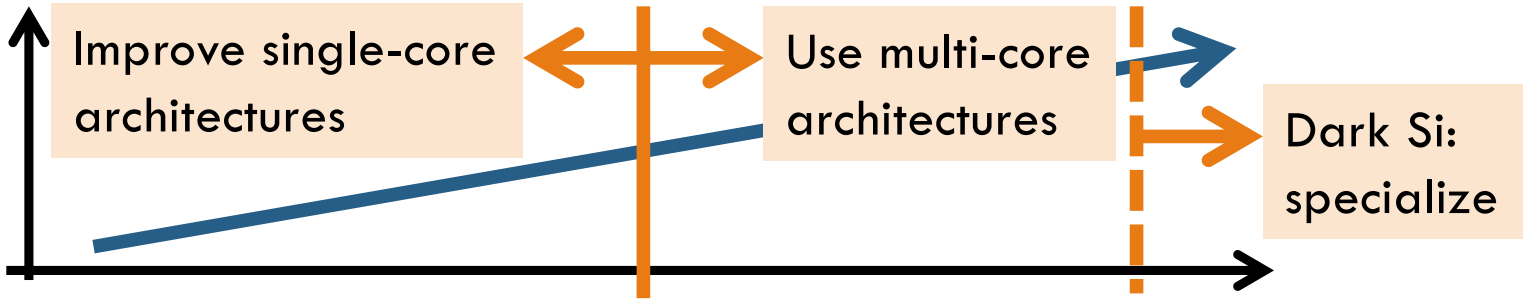
Diminishing returns for single core

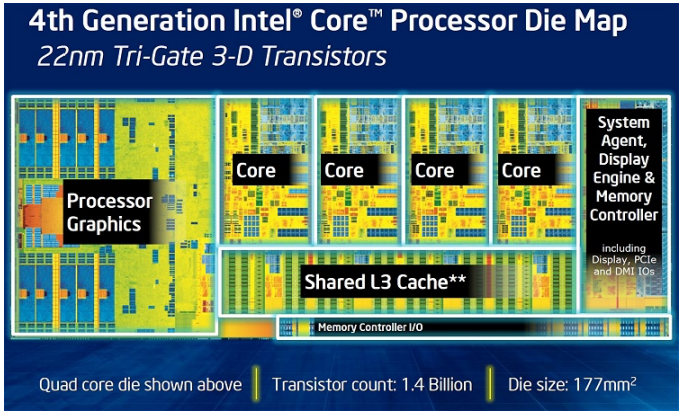
Power density!



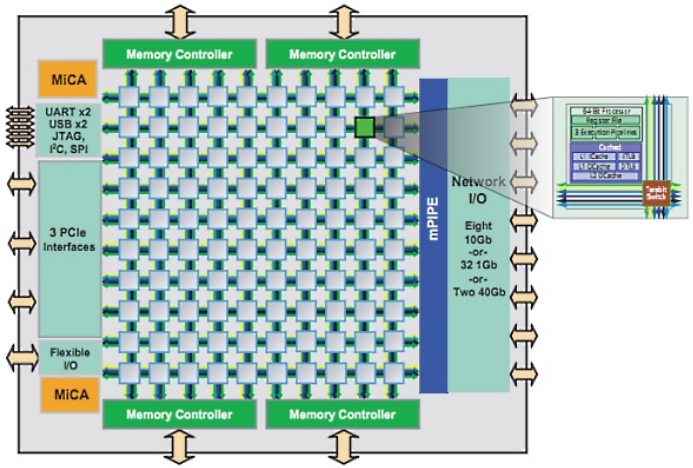
http://www.extremetech.com/computing/112147-hot-chips-laptop-manufacturer-sues-amd-over-allegedly-defective-chips

Inflection points

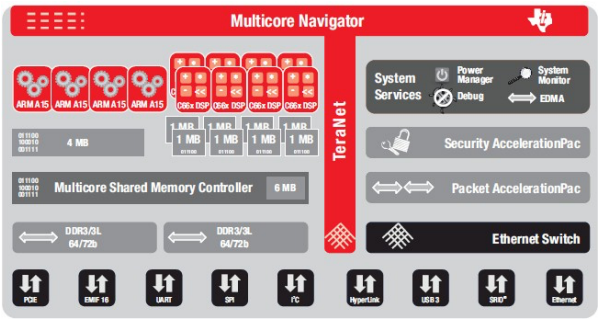




http://www.techspot.com/photos/article/679-intel-haswell-core-i7-4770k/#Slide_01

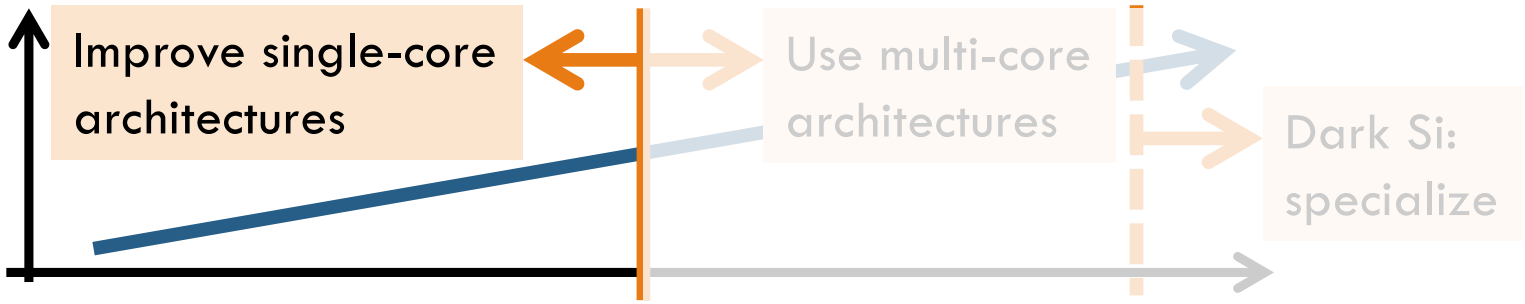


Tilera.com

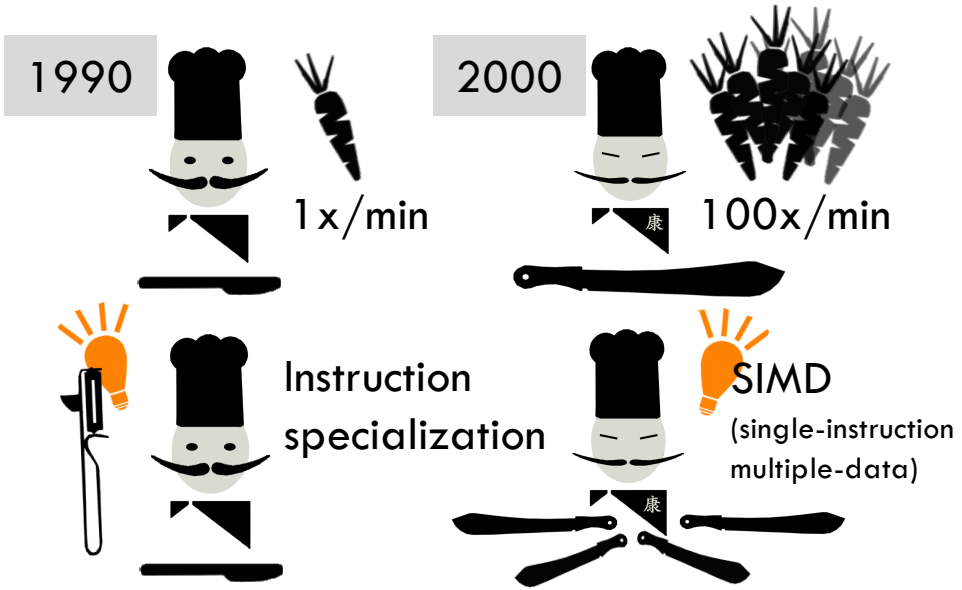


http://www.theregister.co.uk/2013/03/05/hp_moonshot_server_ti_keystone_arm_chip/

What to do with the transistors?



- Mostly transparent for programmers
  - Faster, specialized ISA
  - Incremental compiler innovation



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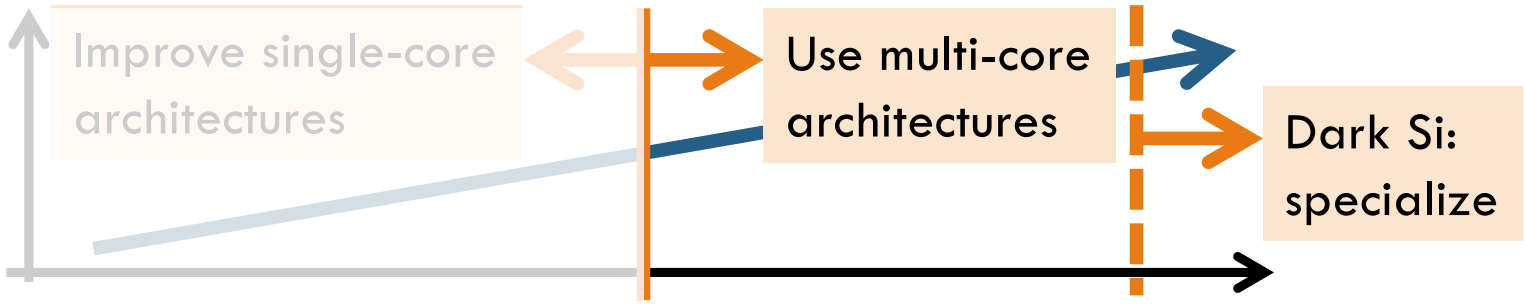
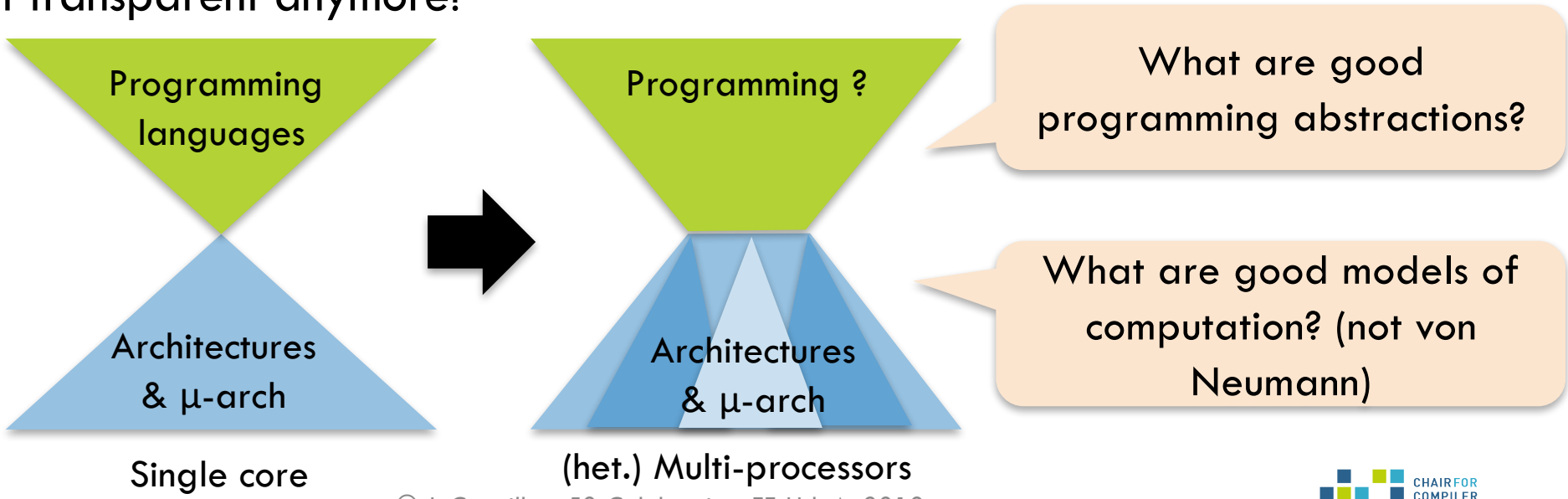


- Not transparent anymore!



Agenda

- Introduction
- Programming models: Overview
- Systematic parallel programming
- Future electronics
- Wrap-up

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Keep it sequential

- Parallel programming is hard (with most abstractions) – more on this later
  - Let the compiler do the work

> **Theorem** (Allen/Kennedy): Any reordering transformation that preserves every dependence in a program preserves the meaning of that program

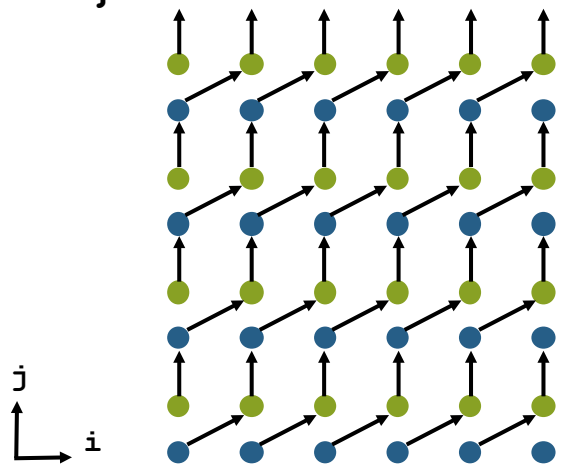
"Optimizing Compilers for Modern Architectures: A Dependence-Based Approach", Allen and Kennedy, 2002, Ch. 2.

Problems for auto-parallelizing compilers

1) Find all dependencies?

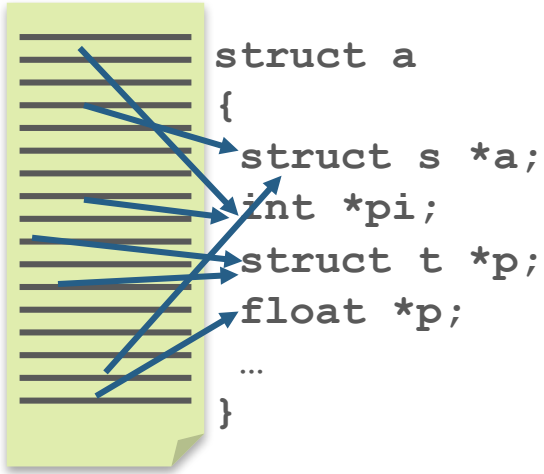
More often than not, impossible!

```
   for (i = 1; i <= 100; i++)
      for (j = 1; j <= 100; j++) {
S1:     X[i][j] = X[i][j] + Y[i-1][j];
S2:     Y[i][j] = Y[i][j] + X[i][j-1];
      }
```



Example: **Polyhedral compilation**

2) Coding style and the illusion of infinite shared memory



Problems for auto-parallelizing compilers

1) Find all dependencies?

2) Coding style and the illusion of infinite shared memory

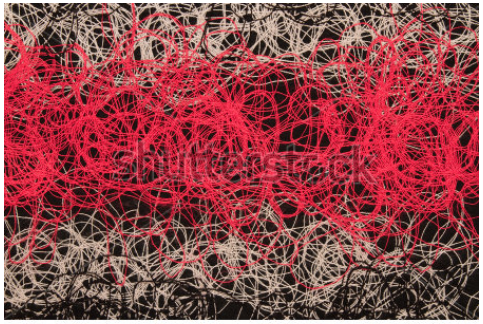
3) Dependencies can sometimes be violated! (they are artifacts of style)

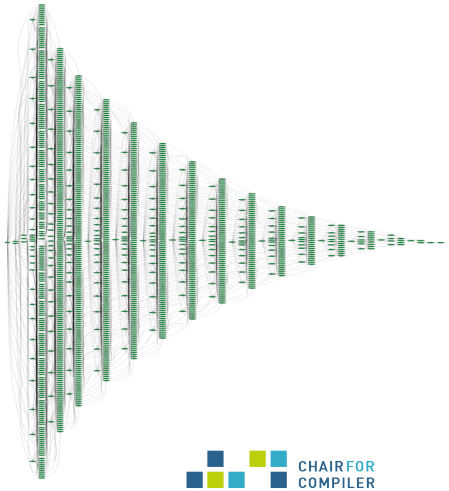
```
19  while(!queue.empty())
20  {
21    // Dequeue a vertex from queue
22    s = queue.front();
23    queue.pop_front();
24
25    // Apply function f to s, accumulate values
26    result += f(s);
27
28    // Get all adjacent vertices of s.
29    // If an adjacent node hasn't been visited,
30    // then mark it as visited and enqueue it
31    for(i=adj[s].begin(); i!=adj[s].end(); ++i)
32    {
33      if(!visited[*i])
34      {
35        visited[*i] = true;
36        queue.push_back(*i);
37      }
38    }
39  }
40
41  return result;
42 }
```

T. J.K. Edler von Koch, S. Manilov, C. Vasiladiotis, M. Cole, and B.Franke. Towards a Compiler Analysis for Parallel Algorithmic Skeletons. In: Proceedings of the 2018 International Conference on Compiler Construction (CC'18), Vienna, 2018.

Options for parallel programming

- Myriads of options: languages, libraries, run-time systems, …
- Shared-memory programming
  - Pthreads, OpenMP, …
  - Task-based programing (Intel TBB, Cilk)
- Distributed-memory programming
  - Message Passing Interface (MPI)
  - Map-Reduce





Options for parallel programming

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Threads: assembly of parallel programming, hard to get it right

OpenMP: Convenient abstraction of threads

Task-based: More abstract – focus on application parallelism

MPI: 400+ APIs – Need a PhD

M&R: More abstract – works great if application adheres to skeleton

Options for parallel programming

- Myriads of options: languages, libraries, run-time systems, …
  - Pthreads, OpenMP, …
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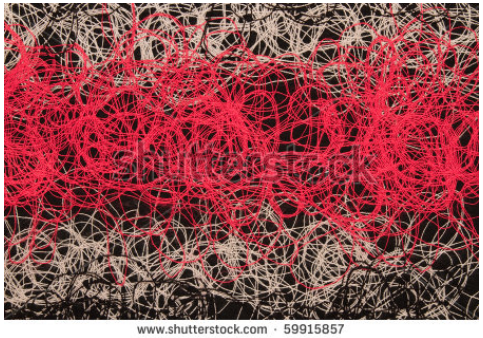
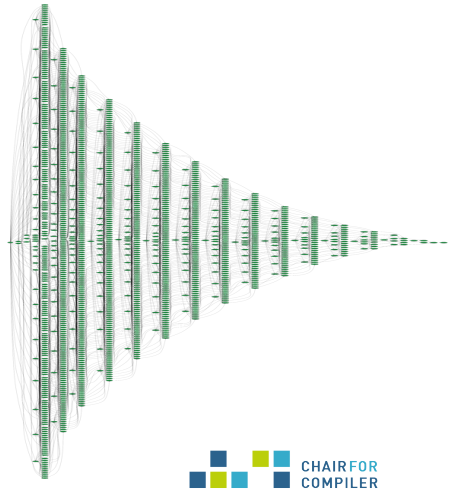


Some models better than others, but still too much of the architecture percolates to programmers (i.e. false sharing, load imbalances, …)



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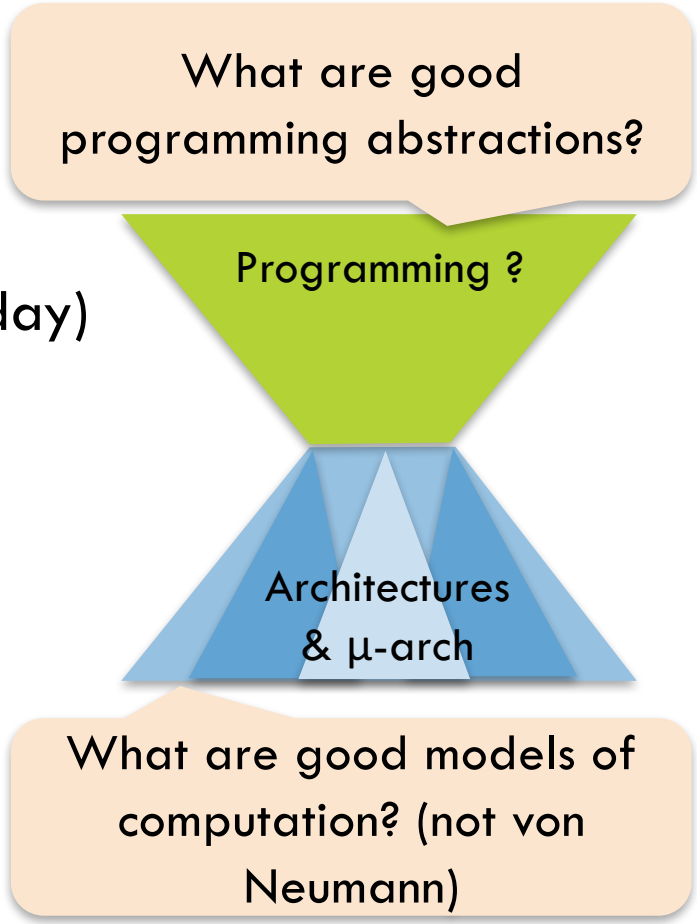
Systematic programming

- Better programming abstractions: No silver bullet
  - Broad spectrum (not GPP): Dataflow
  - Narrow spectrum: Domain-specific languages
- Models of architectures: Whole topic in itself (not today)

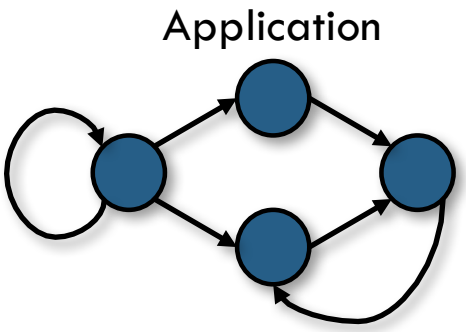
```
-<Platform>
   <Processors List="dsp0 dsp1 dsp2 dsp3 dsp4 dsp5 dsp6 dsp7"/>
   <Memories List="local_mem_dsp0_L2 local_mem_dsp1_L2 local_mem_dsp2_L2 local_mem_dsp
   local_smem_dsp1_L2 local_smem_dsp2_L2 local_smem_dsp3_L2 local_smem_dsp4_L2 local_smem
   local_mem_dsp3_DDR local_mem_dsp4_DDR local_mem_dsp5_DDR local_mem_dsp6_DDR local_m
   <CommPrimitives List="IPCll_SL2 IPCll_DDR EDMA3_SL2 EDMA3_DDR EDMA3_LL2"/>
 </Platform>
 <Processor Name="dsp0" CoreRef="DSPC66"/>
 <Processor Name="dsp1" CoreRef="DSPC66"/>
     ...
 <Processor Name="dsp7" CoreRef="DSPC66"/>
-<Memory>
   <LocalMemory Name="local_mem_dsp0_L2" Size="524288" BaseAddress_hex="00800000"
 </Memory>
     ...
```

- Systematic: Use automation (SW tools) to **lower the high-level spec to the hardware**



Broad: Dataflow programming

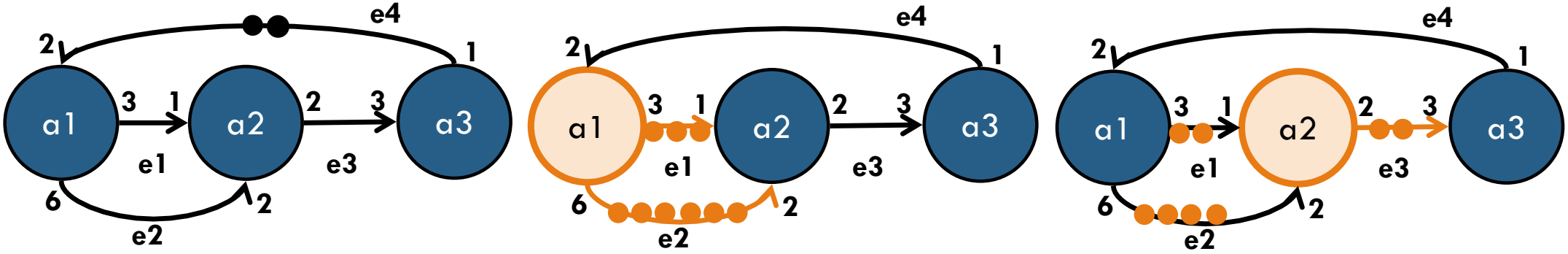
- Graph representation of applications
  - Nodes represent computation
  - Edges represent communication
  - Multiple variations of the precise semantics proposed



- Popular abstraction in many domains
  - Embedded signal processing
  - High-performance computing (OmpSs → OpenMP 4.5)
  - Databases
  - Big-data processing pipelines

Dataflow programming: Systematic

- Intuition for simple case: Synchronous Dataflow (SDF)



$$\Gamma = \begin{pmatrix} 3 & -1 & 0 \\ 6 & -2 & 0 \\ 0 & 2 & -3 \\ -2 & 0 & 1 \end{pmatrix}$$

$$s_2 = s_1 + \begin{pmatrix} 3 & -1 & 0 \\ 6 & -2 & 0 \\ 0 & 2 & -3 \\ -2 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 2 \\ 4 \\ 2 \\ 0 \end{pmatrix}$$

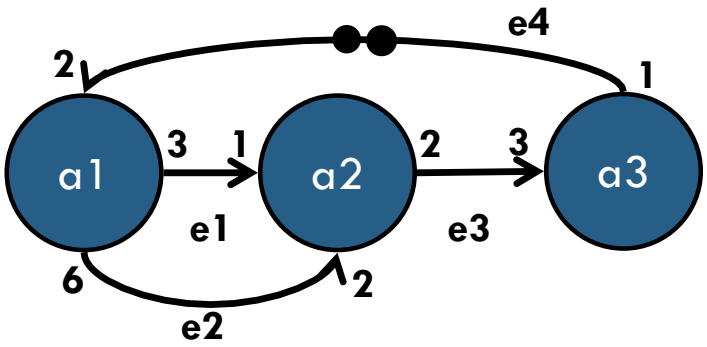
$$s_1 = s_0 + \begin{pmatrix} 3 & -1 & 0 \\ 6 & -2 & 0 \\ 0 & 2 & -3 \\ -2 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 2 \end{pmatrix} + \begin{pmatrix} 3 \\ 6 \\ 0 \\ -2 \end{pmatrix} = \begin{pmatrix} 3 \\ 6 \\ 0 \\ 0 \end{pmatrix}$$

Lee, E. A. & Messerschmitt, D. G. Synchronous Data Flow. Proceedings of the IEEE, 1987, 75, 1235-1245

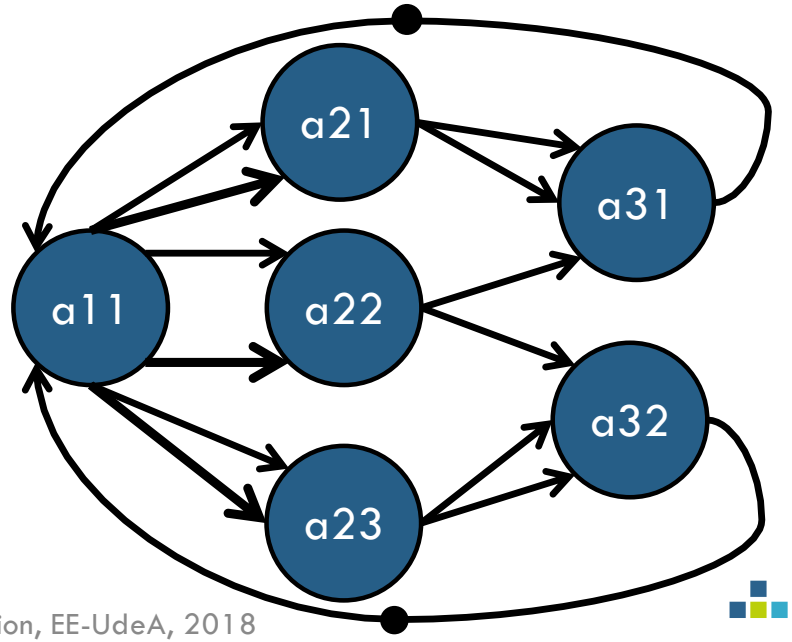
Dataflow programming: Systematic (2)

- Intuition for simple case: Synchronous Dataflow (SDF)
- Consequence
  - Possible to guarantee deadlock-freedom and execution on bounded memory
  - Possible to compute static schedule and optimize for throughput, energy, …

$$\Gamma \cdot (v_1 + v_2 + \cdots + v_n) = \Gamma \cdot \vec{r} = 0$$

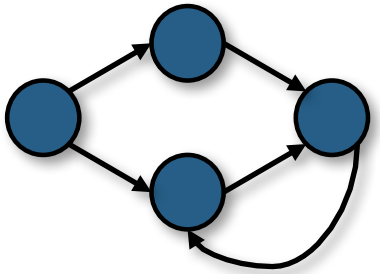


$$\vec{r} = (1, 3, 2)^T$$

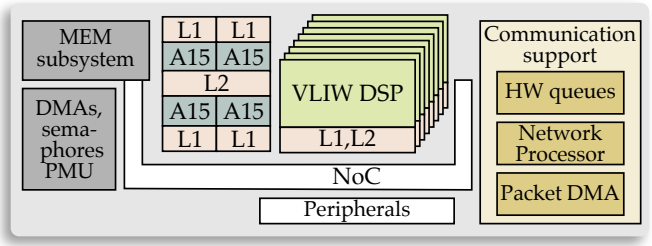


Dataflow programming flow

Application



Architecture model



Non-functional specification

[Castrill11, Castrill13, Castrill14]

Analysis

Synthesis

Property models (timing, energy, error, …)

Configurations

Source-to-source compilation

```
PNargs_ifft_r.ID = 6U;
   PNargs_ifft_r.PNchannel_freq_coef = filtered_coef_r
   PNargs_ifft_r.PNnum_freq_coef = 0U;
   PNargs_ifft_r.PNchannel_time_coef = sink_right;
   PNargs_ifft_r.channel = 1;
   sink_left = IPCllmrf_open(3, 1, 1);
   sink_right = IPCllmrf_open(7, 1, 1);
   PNargs_sink.ID = 7U;
   PNargs_sink.PNchannel_in_left = sink_left;
   PNargs_sink.PNnum_in_left = 0U;
   PNargs_sink.PNchannel_in_right = sink_right;
   PNargs_sink.PNnum_in_right = 0U;
   taskParams.arg0 = (xdc_UArg)&PNargs_src;
   taskParams.priority = 1;
```

Narrow: Domain-specific languages

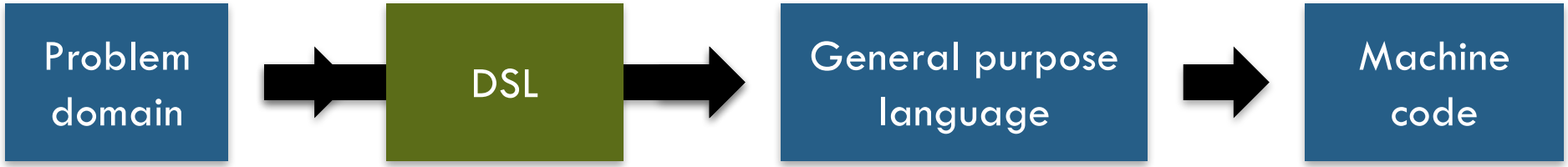
- Languages as abstractions

```
f(x) {...}
```

Source: https://en.wikipedia.org/wiki/Calling_convention

```
calc:
  push EBP ; save old frame pointer
  mov  EBP,ESP ; get new frame pointer
  sub ESP,localsize ; reserve place for locals
  ... ; perform calculations, leave result in EAX
  mov ESP,EBP ; free space for locals
  pop EBP ; restore old frame pointer
  ret paramsize ; free parameter space and return
```

- DSLs: bridge gap between problem domain and general purpose languages



Adapted from lecture: "Concepts of Programming Languages", Eelco Visser, TU Delft

  - Why today? SW becoming pervasive, systems more complex, …

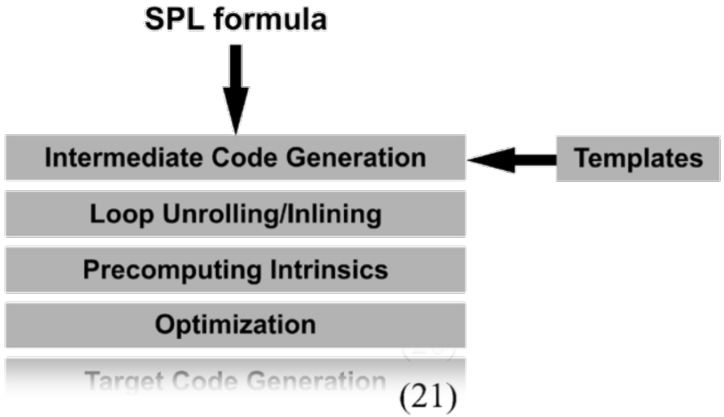
DSLs examples

- There are many examples, already for many years
  - Regexp in linux
  - SQL for databases
- Closer to my topics
  - Spiral (CMU/ETHZ): for linear transformations
  - TensorFlow (Google): for machine learning
  - Firedrake (Imperial College): for finite elements methods

Spiral

- Exploit **structure of known matrixes** to perform automatic algebraic transformations (e.g., factorization)

$$\mathbf{DCT\text{-}2}_n \rightarrow L^n_m(\mathbf{DCT\text{-}2}_m \oplus \mathbf{DCT\text{-}4}_m) \cdot (F_2 \otimes I_m)(I_m \oplus J_m)$$



- Rewrite rules to produce different variants

$$\mathbf{DFT}_n \rightarrow P_n(\mathbf{DFT}_k \otimes \mathbf{DFT}_m)Q_n, \quad n = km,\ \gcd(k,m) = 1 \tag{21}$$

$$\mathbf{DFT}_p \rightarrow R_p^T(\mathrm{I}_1 \oplus \mathbf{DFT}_{p-1})D_p(\mathrm{I}_1 \oplus \mathbf{DFT}_{p-1})R_p, \quad p \text{ prime} \tag{22}$$

$$\mathbf{DCT\text{-}3}_n \rightarrow (\mathrm{I}_m \oplus \mathrm{J}_m)\,\mathrm{L}^n_m(\mathbf{DCT\text{-}3}_m(1/4) \oplus \mathbf{DCT\text{-}3}_m(3/4))(\mathrm{F}_2 \otimes \mathrm{I}_m)\begin{bmatrix} \mathrm{I}_m & 0 \oplus -\mathrm{J}_{m-1} \\ \frac{1}{\sqrt{2}}(\mathrm{I}_1 \oplus 2\,\mathrm{I}_m) \end{bmatrix}, \quad n = 2m \tag{23}$$

$$\mathbf{DCT\text{-}4}_n \rightarrow S_n\mathbf{DCT\text{-}2}_n\,\mathrm{diag}_{0\le k<n}\left(1/(2\cos\tfrac{(2k+1)\pi}{4n})\right) \tag{24}$$

$$\mathbf{IMDCT}_{2m} \rightarrow (\mathrm{J}_m \oplus \mathrm{I}_m \oplus \mathrm{I}_m \oplus \mathrm{J}_m)\left(\begin{bmatrix} 1 \\ -1 \end{bmatrix} \otimes \mathrm{I}_m\right) \oplus \left(\begin{bmatrix} -1 \\ -1 \end{bmatrix} \otimes \mathrm{I}_m\right) \mathrm{J}_{2m}\,\mathbf{DCT\text{-}4}_{2m} \tag{25}$$

Püschel, M.; Moura, J.; Johnson, J.; Padua, D.; Veloso, M.; Singer, B.; Xiong, J.; Franchetti, F.; Gacic, A.; Voronenko, Y.; Chen, K.; Johnson, R. & Rizzolo, N. SPIRAL: Code Generation for DSP Transforms. Proceedings of the IEEE, 2005, 93, 232 -275

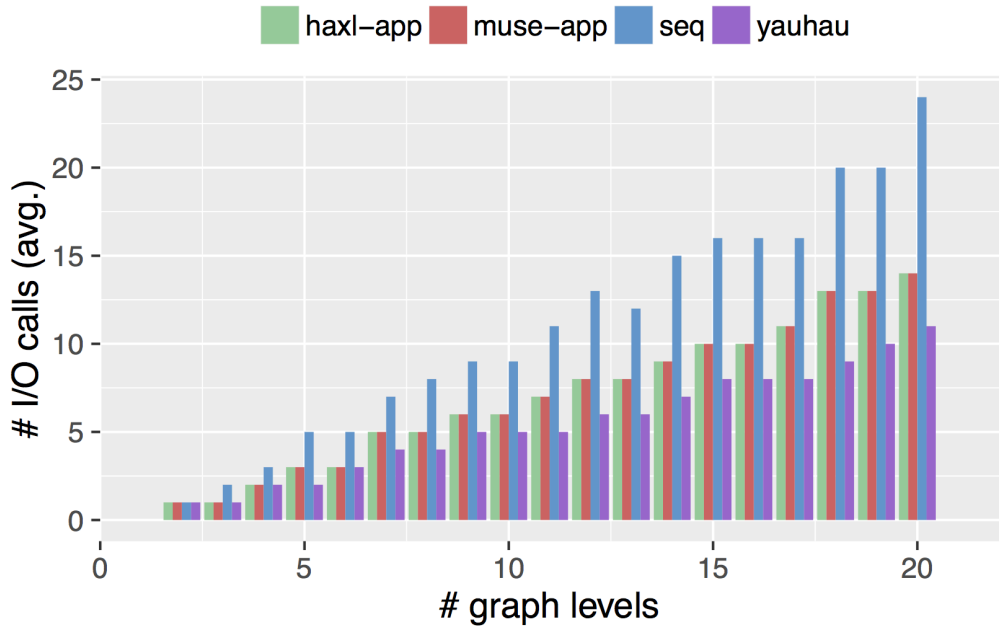
Ohua

- Ohua: Functional programming abstraction to implicitly create dataflow graphs
  - Functional program: High-level algorithm (clojure)
  - State-full functions: actual application logic (clojure, java, scala, …)

```
1  (ohua :import [web.translation]) ; import the namespace where the used
2                                   ; functions are defined
3  (defn translate [server-port]
4    (ohua (let [[cnn req] (read-socket (accept (open server-port)))
5                [_ file-name _ lang] (parse-request req)
6                [^List content length] (if (exists? file-name)
7                                           (load-file-from-disk file-name)
8                                           (generate-reply "No such file."))
9                ^String word (decompose content) ; poor man's translation
10               _ (log "translating word")
11               updated-content (collect length (translate word lang))]
12           (reply cnn (compose length updated-content)))
```

Ohua applications: Micro-services

- Automatic batching of I/O in micro-services: Via graph rewrites
- Similar performance than e.g., Facebook, with better code style



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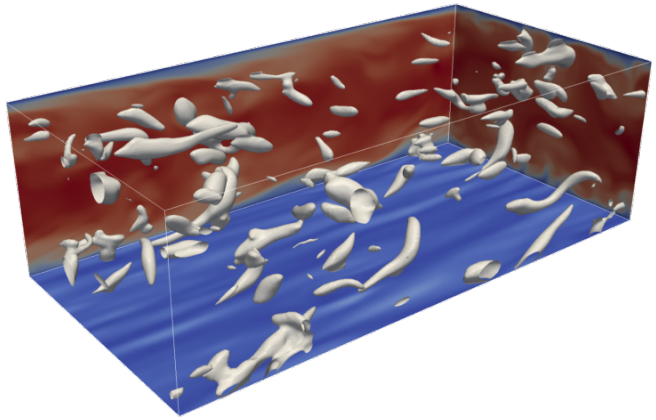
CFDlang for computational fluid dynamics (CFD)



- Tensor expressions typically occur in numerical codes

$$\mathbf{v}_e = (\mathbf{A} \otimes \mathbf{A} \otimes \mathbf{A})\, \mathbf{u}_e$$

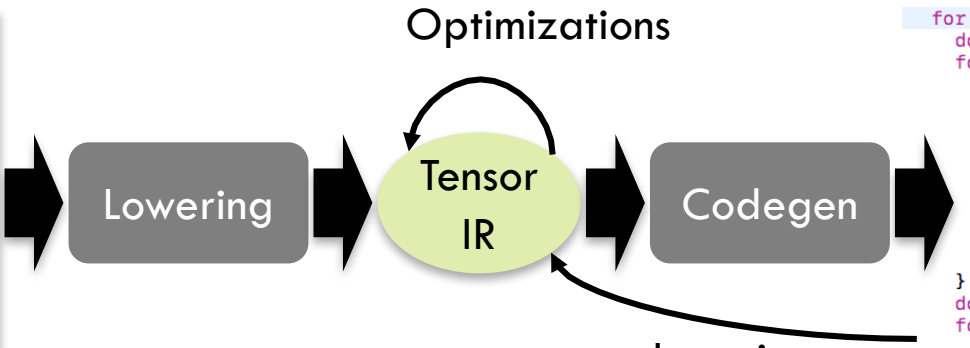
  - Tensor product notation popular in the CFD domain
- On performance
  - Matrixes are small, so libraries like BLAS don't always help
  - Expressions result in deeply nested for-loops
  - Performance highly depend on the *shape* of the loop nests

- **No need to do complex polyhedral analysis if we know the tensors and the semantics of the operators!**

CFDlang and tool flow

```
source =
type matrix    : [mp np]          &
type tensorIN  : [np np np ne]    &
type tensorOUT : [mp mp mp me]    &
                                  &
var input A    : matrix           &
var input u    : tensorIN         &
var input output v  : tensorOUT   &
var input alpha : []              &
var input beta  : []              &
                                  &
v = alpha * (A # A # A # u .
    [[5 8] [3 7] [1 6]]) + beta * v
```

Fortran embedding



Linkable C code

```
for (unsigned i0 = 0; i0 < 1000; i0++) {
  double t6[18];
  for (unsigned i3 = 0; i3 < 3; i3++) {
    for (unsigned i2 = 0; i2 < 3; i2++) {
      for (unsigned i1 = 0; i1 < 2; i1++)
        t6[(i1 + 2*(i2 + 3*(i3)))] = 0.0;
        for (unsigned i4_contr = 0; i4_contr < 3; i4_contr++) {
          t6[(i1 + 2*(i2 + 3*(i3)))] += A[(i1 + 2*(i4_contr))]
              * u[(i2 + 3*(i3 + 3*(i4_contr + 3*(i0))))];
        }
      }
    }
  }
  double t7[12];
  for (unsigned i7 = 0; i7 < 3; i7++) {
    for (unsigned i6 = 0; i6 < 2; i6++) {
      for (unsigned i5 = 0; i5 < 2; i5++) {
        t7[(i5 + 2*(i6 + 2*(i7)))] = 0.0;
        for (unsigned i8_contr = 0; i8_contr < 3; i8_contr++) {
          t7[(i5 + 2*(i6 + 2*(i7)))] += A[(i5 + 2*(i8_contr))]
              * t6[(i6 + 2*(i7 + 3*(i8_contr)))];
        }
      }
    }
  }
  double t8[1];
  double t9[1];
  for (unsigned i11 = 0; i11 < 2; i11++) {
    for (unsigned i10 = 0; i10 < 2; i10++) {
      for (unsigned i9 = 0; i9 < 2; i9++) {
        t9[0] = 0.0;
        for (unsigned i12_contr = 0; i12_contr < 3; i12_contr++
            ) {
          t9[0] += A[(i9 + 2*(i12_contr))] * t7[(i10 + 2*(i11 +
              2*(i12_contr)))];
        }
        t8[0] = alpha[0] * t9[0];
        double t10[1];
        t10[0] = beta[0] * v[(i9 + 2*(i10 + 2*(i11 + 2*(i0))))]
            ;
        v[(i9 + 2*(i10 + 2*(i11 + 2*(i0))))] = t8[0] + t10[0];
      }
    }
  }
}
```

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Example: Interpolation operator

- Interpolation: $\mathbf{v}_e = (\mathbf{A} \otimes \mathbf{A} \otimes \mathbf{A})\, \mathbf{u}_e$

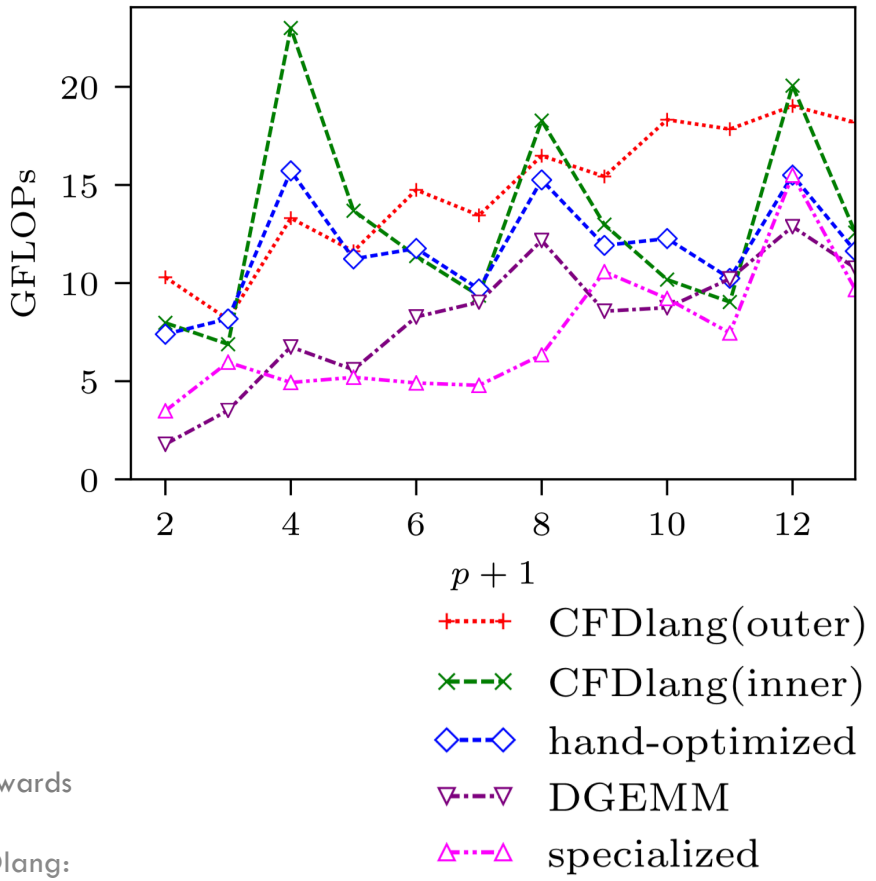
$$v_{ijk} = \sum_{l,m,n} A_{kn} \cdot A_{jm} \cdot A_{il} \cdot u_{lmn}$$

- Three alternative orders (besides naïve)

E1: $$v_{ijk} = \sum_{l,m,n} (A_{kn} \cdot (A_{jm} \cdot (A_{il} \cdot u_{lmn}))$$

E2: $$v_{ijk} = \sum_{l,m,n} (A_{kn} \cdot A_{jm}) \cdot (A_{il} \cdot u_{lmn})$$

E3: $$v_{ijk} = \sum_{l,m,n} (A_{kn} \cdot ((A_{jm} \cdot A_{il}) \cdot u_{lmn}))$$



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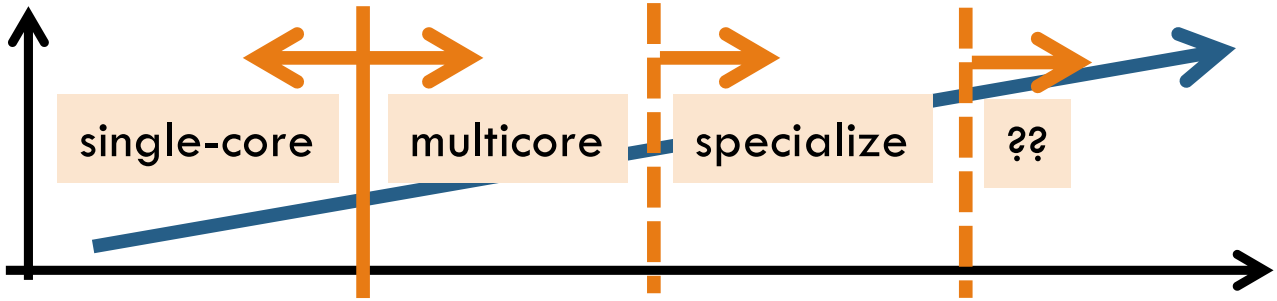
Agenda

- Introduction
- Programming models: Overview
- Systematic parallel programming
- **Future electronics**
- Wrap-up

Extreme heterogeneity



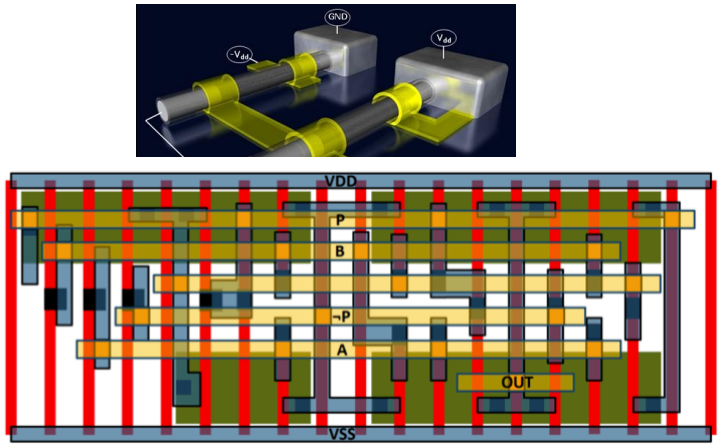
- Inflection points
  - End of frequency scaling: Multicores
  - End of Dennard scaling and power density: heterogeneous systems
  - Physical limits of CMOS: Extreme heterogeneity (new materials, new paradigms)

- Many ideas: quantum, neuromorphic, protein-based, DNA storage, spin-orbit-tronics, organic, …

Context: Center for advancing electronics Dresden (2)

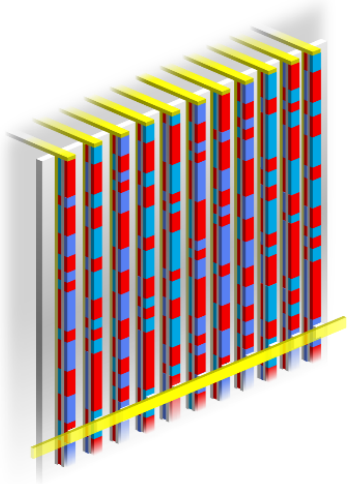
- Sample technologies

Novel transistor reconfigurability



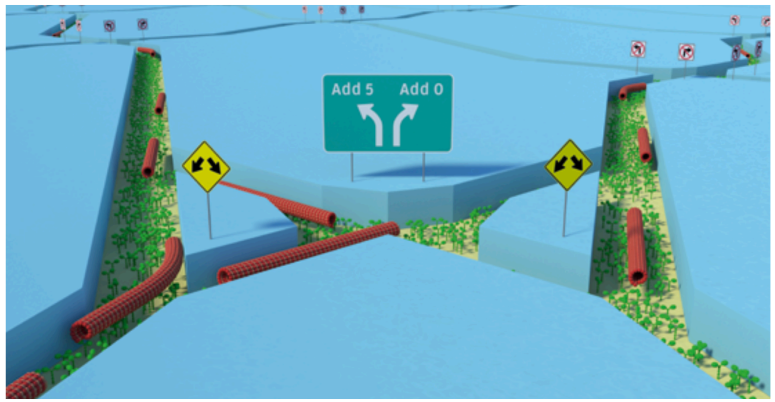
M. Raitza, et al., "Exploiting Transistor-Level Reconfiguration to Optimize Combinational Circuits" , DATE 2017

Spin-orbit Racetracks



Parkin, US patents 6834005, 6898132.
Parkin et al., Science 320, 190 (2008).
Parkin, Scientific American (2009).

Protein-based computing



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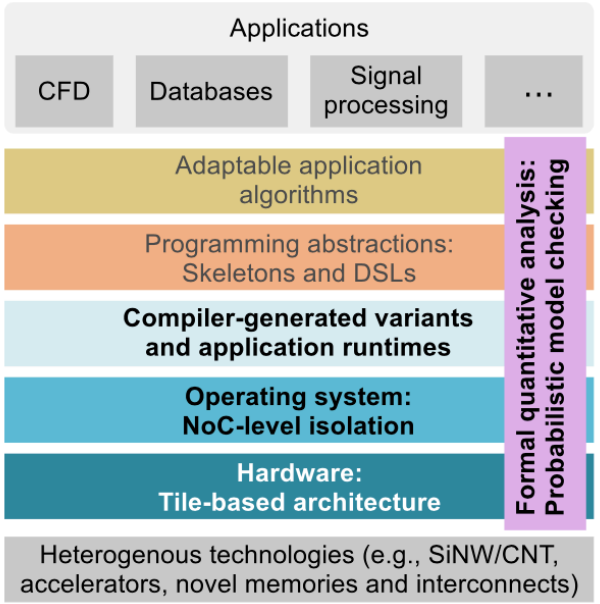
SW for extreme heterogeneity

- Working on principles for a programming stack
- Programming abstractions
  - High-level: DSLs
  - Lower-level: Dataflow execution models
- Execution abstractions
  - Application runtimes for adapativity
  - Micro-kernel based OSes



J. Castrillon, et al. "A Hardware/Software Stack for Heterogeneous Systems". IEEE TMSCS, 2017

- Requires models: SW people require closer communication with technologists!

SW for extreme heterogeneity (2)

- Working on principles for a programming
- Programming abstractions
  - High-level: DSLs
  - Lower-level: Dataflow execution models
- Execution abstractions
  - Application runtimes for adapativity
  - Micro-kernel based OSes

Report from Dagstuhl Seminar 17061

Wildly Heterogeneous Post-CMOS Technologies Meet Software

Edited by

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Abstract

The end of exponential scaling in conve
years by now. While advances in fab
predicted, the so anticipated end seems t
"Wildly Heterogeneous Post-CMOS Tec
material research, hardware componen
systems. By bringing together experts
interdisciplinarily across fields, the sem
challenges of advancing computing bey
visions about a future hardware/softwa

- **Requires models: SW people require closer communication with technologists!**

Agenda

- Introduction
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Wrap-up

- Discussed facts that continue to lead innovation in electronics
- Need for abstractions and models: Software research
  - Examples: DSLs and dataflow models
- Cfaed: Next inflection point in computing? → makes things even more challenging (and exciting!)
  - Research opportunities on computer architecture (open source simulators)
- What will be talking about at the 100 year's celebration?
  - I believe EE students can play a pivotal role

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