Innovative Applications and Technology Pivots – A Perfect Storm in Computing

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Agenda

- Revolutionary paradigm shift in applications
- Post-Dennard technology pivot
- Engineering high-efficiency scalable algorithm libraries for heterogeneous parallel computing

A major paradigm shift

- **In the 20th Century, we were able to understand, design, and manufacture what we can measure**
  - Physical instruments and computing systems allowed us to see farther, capture more, communicate better, understand natural processes, control artificial processes…

A major paradigm shift

- In the 20th Century, we were able to understand, design, and manufacture what we can measure
  - Physical instruments and computing systems allowed us to see farther, capture more, communicate better, understand natural processes, control artificial processes…
- **In the 21st Century, we are able to understand, design, and create what we can compute**
  - Computational models are allowing us to see even farther, going back and forth in time, learn better, test hypothesis that cannot be verified any other way, create safe artificial processes…

Examples of Paradigm Shift

20th Century

- Small mask patterns
- Electronic microscope and Crystallography with computational image processing
- Anatomic imaging with computational image processing
- Teleconference
- GPS

21st Century

- Optical proximity correction
- Computational microscope with initial conditions from Crystallography
- Metabolic imaging sees disease before visible anatomic change
- Tele-emersion
- Self-driving cars

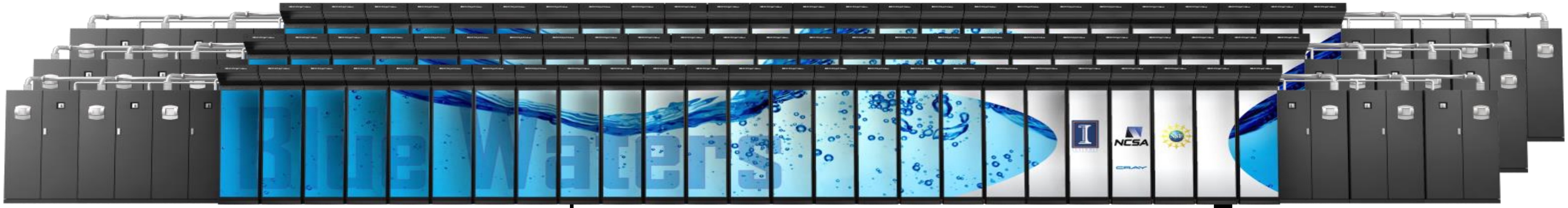
What is powering the paradigm shift?

- Large clusters (scale out) allow solving realistic problems
  - 1.5 Peta bytes of DRAM in Blue Waters
  - E.g., 0.5 Å (0.05 nm) grid spacing is needed for accurate molecular dynamics
    - interesting biological systems have dimensions of mm or larger
    - Thousands of nodes are required to hold and update all the grid points.
- Fast nodes (scale up) allow solution at realistic time scales
  - Simulation time steps at femtosecond (10^{-15} second) level needed for accuracy
    - Biological processes take milliseconds or longer
    - Current molecular dynamics simulations progress at about one day for each 100 microseconds of the simulated process.
    - Interesting computational experiments take weeks (used to be months)

Blue Waters Computing System

Operational at Illinois since 3/2013

49,504 CPUs -- 4,224 GPUs



12.5 PF
1.6 PB DRAM
$250M

10/40/100 Gb Ethernet Switch

IB Switch

>1 TB/sec

120+ Gb/sec

100 GB/sec

WAN

Spectra Logic: 300 PBs

Sonexion: 26 PBs

What types of applications are demanding computing power today?

- First-principle-based models
  - Problems that we know how to solve accurately but chose not to because it would be “too expensive”
  - High-valued applications with approximations that cause inaccuracies and lost opportunities
  - Medicate imaging, earthquake modeling, weather modeling, astrophysics modeling, precision digital manufacturing, combustion modeling, ….

- Applications that we have failed to program
  - Problems that we just don’t know how to solve
  - High-valued applications with no effective computational methods
  - Computer vision, speech processing, stock trading, decision making

Some different modalities of Real-world Data

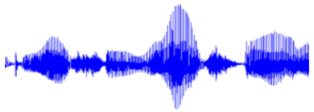
Images/video

Image

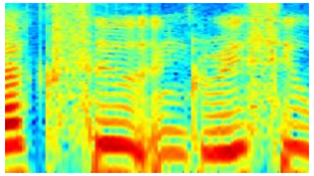
Vision features

Detection

Audio



Audio

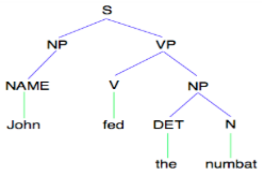


Audio features

Speaker ID

Text

Text

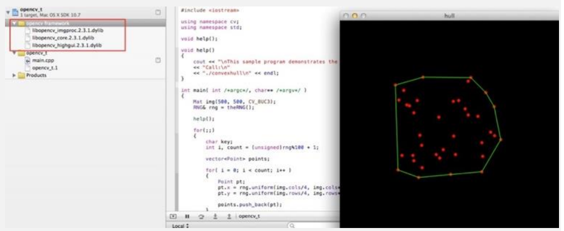


Text features

Text classification, machine translation, information retrieval, ...

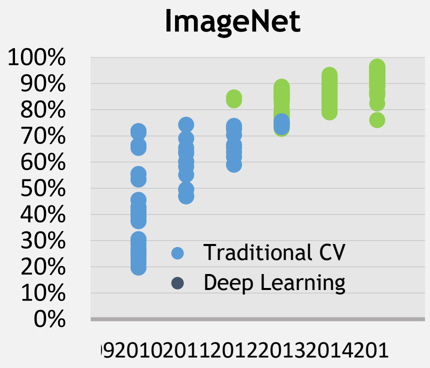
Slide courtesy of Andrew Ng, Stanford University

We know what we want but don’t know how to get there.



Traditional Computer Vision
Experts + Time

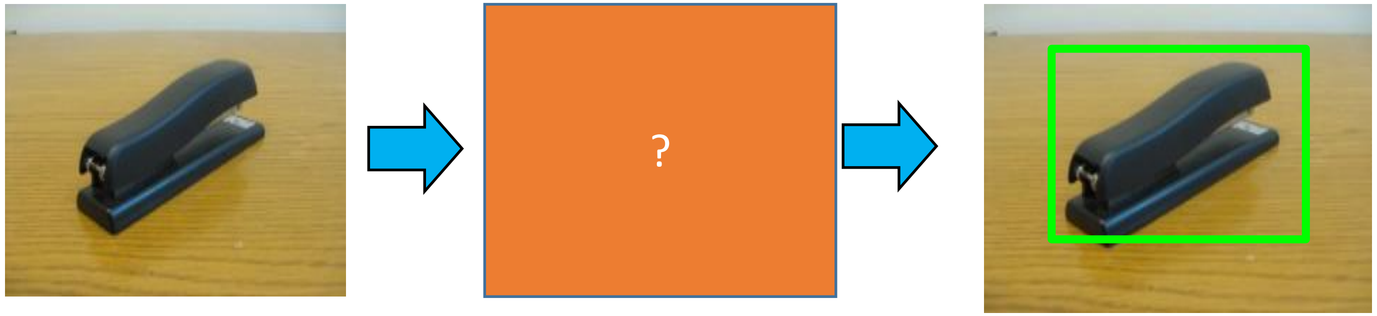
Deep Learning Object Detection
DNN + Data + HPC



Deep Learning Achieves
“Superhuman” Results

Slide courtesy of Steve Oberlin, NVIDIA

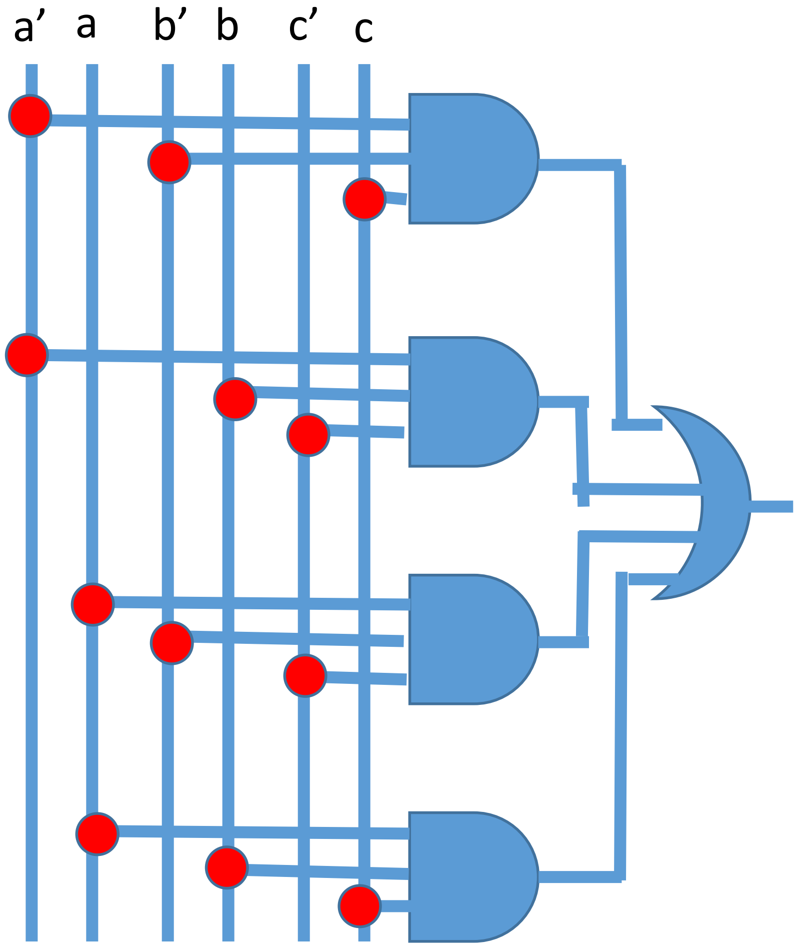
Some different modalities of Real-world Data



This seems to be a combinational logic design problem.

Combinations Logic Specification – Truth Table

Input			output
a	b	c	
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1



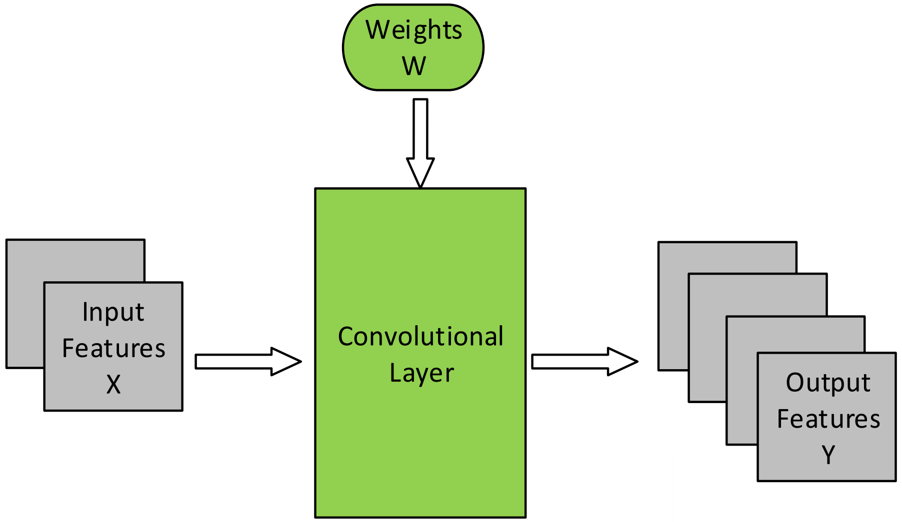
What if we did not know the truth table?

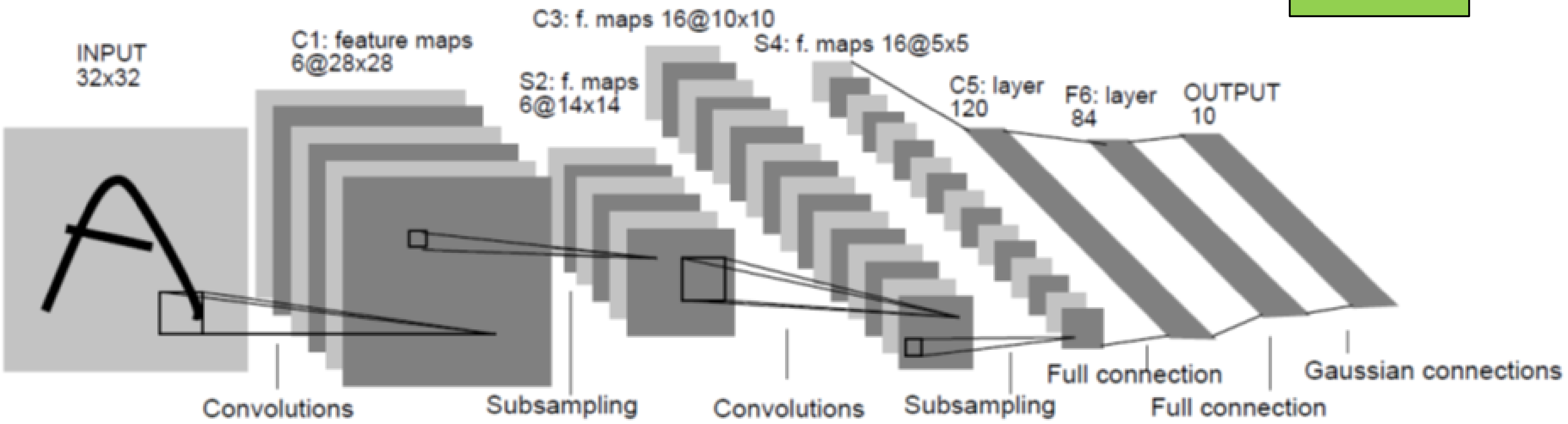
- Look at enough observation data to construct the rules
  - 000 → 0
  - 011 → 0
  - 100 → 1
  - 110 → 0

- If we have enough observational data to cover all input patterns, we can construct the truth table and derive the logic!

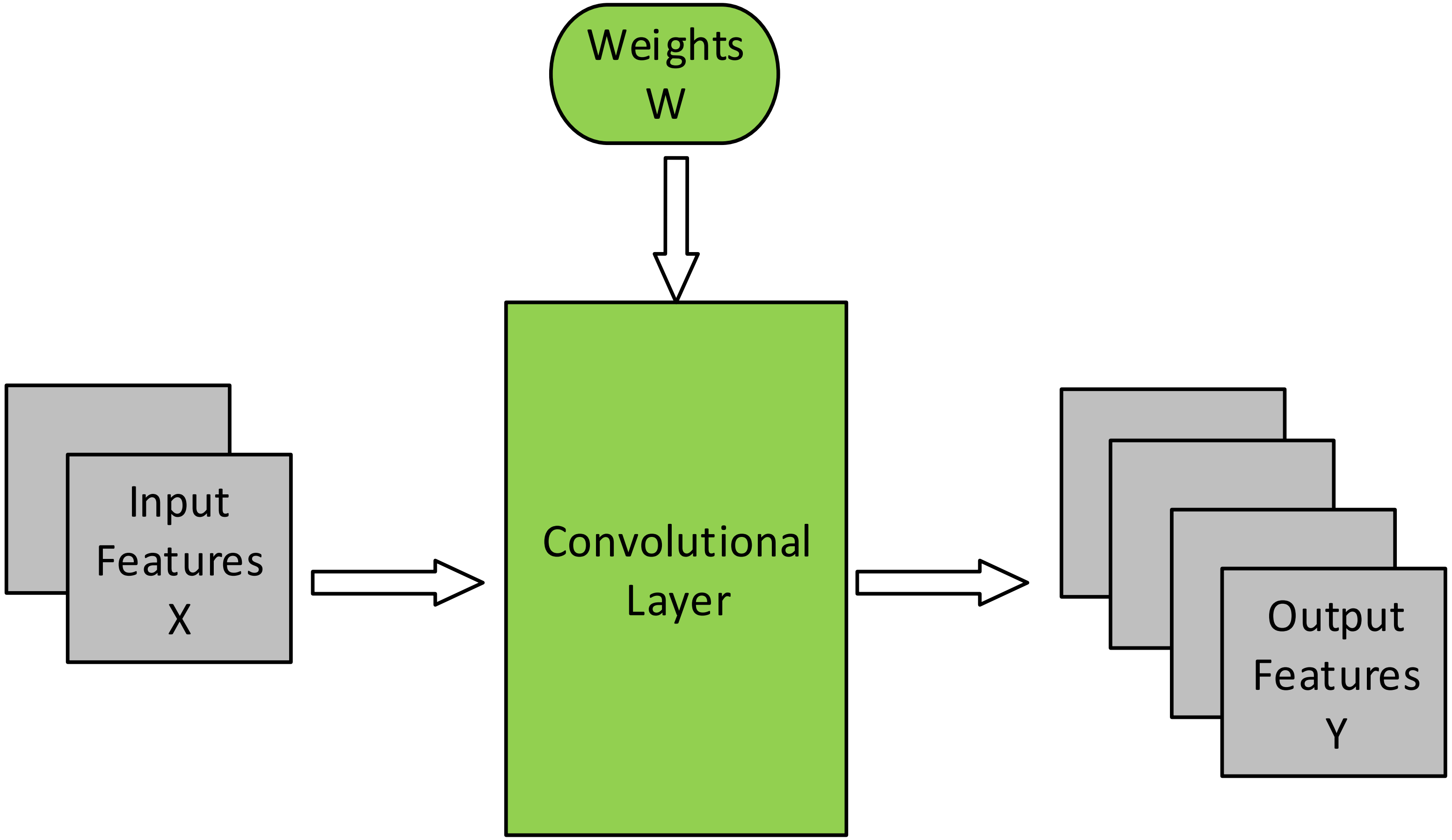
LeNet-5, a convolutional neural network for hand-written digit recognition.

This is a 1024*8 bit input, which will have a truth table of 2 ^{8196} entries

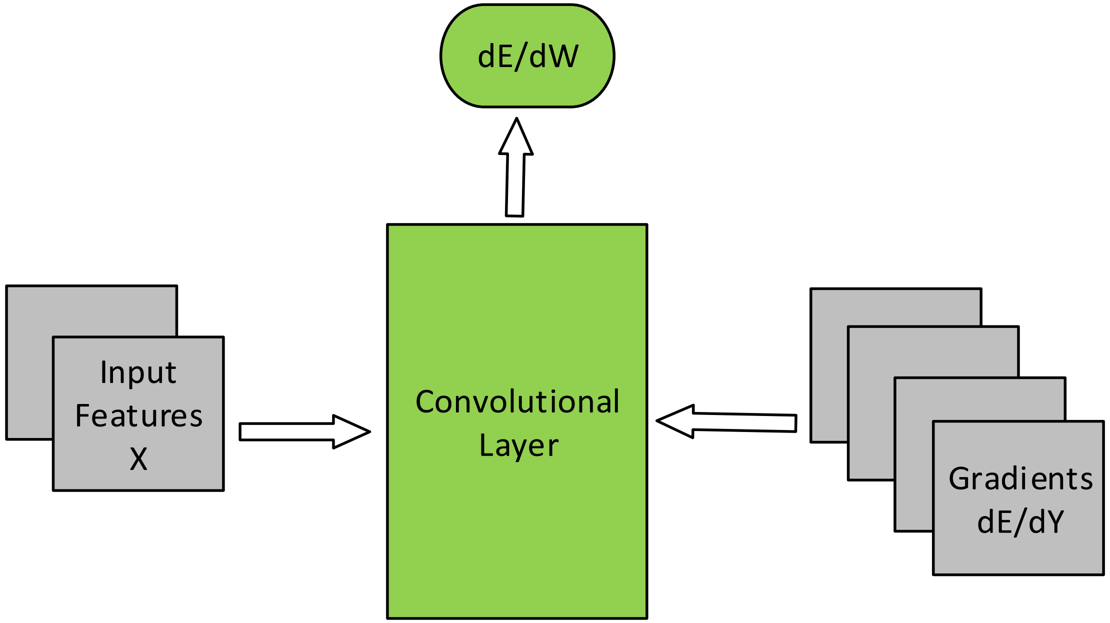




Forward Propagation Path of a Convolution Layer



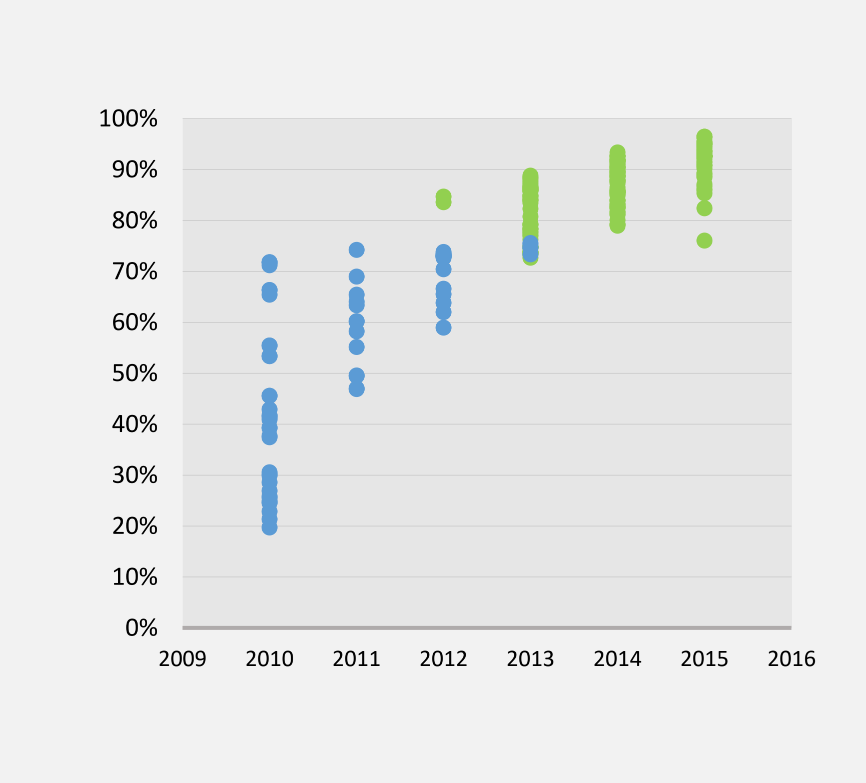
Back-Propagation of $\partial E/\partial W$



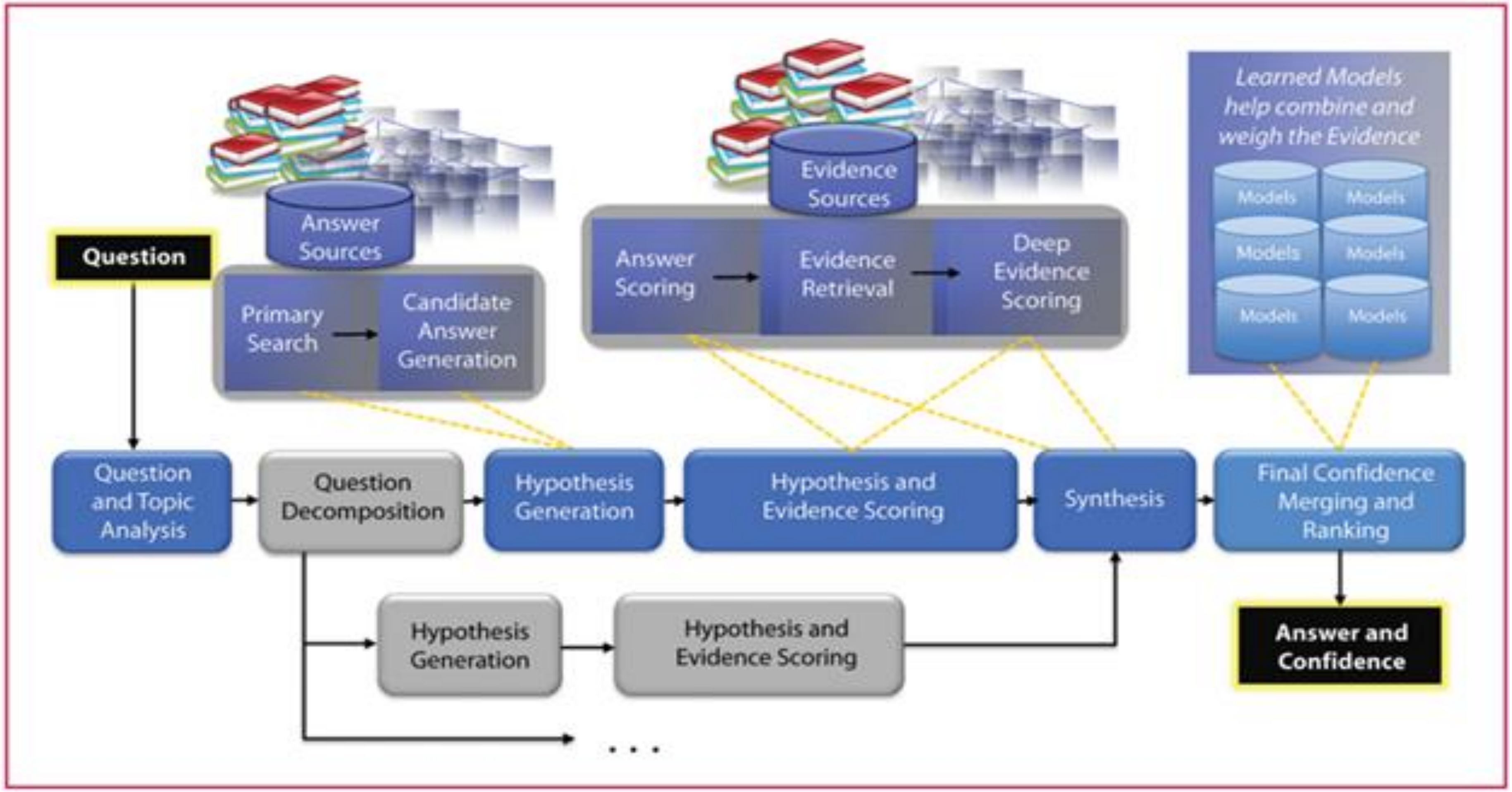
$\partial E/\partial X = W^T * \partial E/\partial Y$ and $\partial E/\partial W = \partial E/\partial Y * X^T$

Behind the Scenes

- In 2010 Prof. Andreas Moshovos adopted the Illinoi ECE498AL Programming Massively Parallel Programming Class
- Several of Prof. Geoffrey Hinton's graduate students took the course
- These students developed the GPU implementation of the DNN that was trained with 1.2M images to win the ImageNet competition



IBM Watson Q&A Pipeline - 2012 Jeopardy! running on a 2,880 node cluster



A long way to go towards cognitive computing

▼ Social Sciences

Use the cartoon to answer the next TWO questions.

24

What economic condition motivated Phil to request a raise?

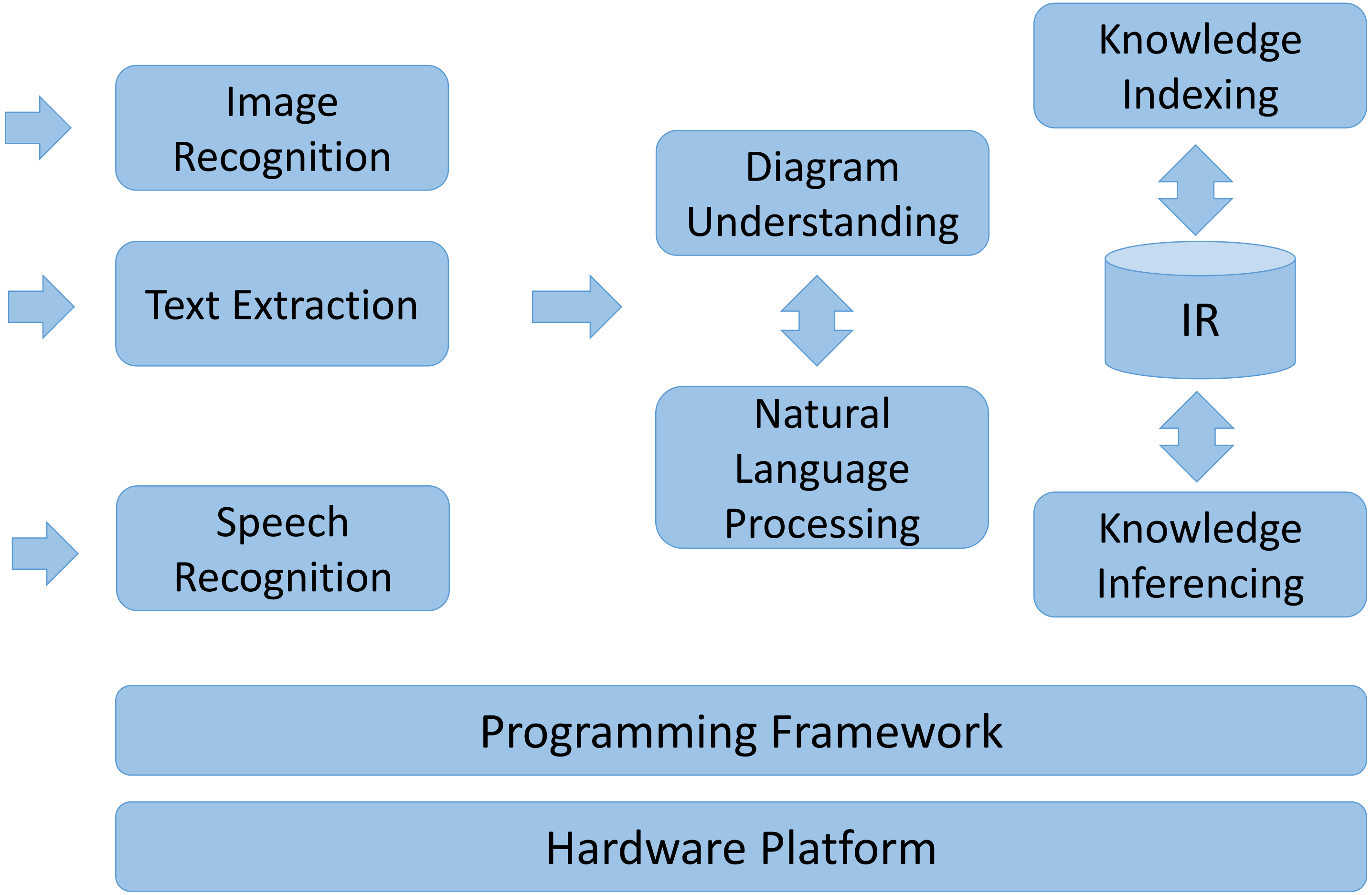
A. Inflation
B. Specialization
C. Unemployment
D. Embargo

25

Without his raise, which would typify Phil's behavior in the marketplace?

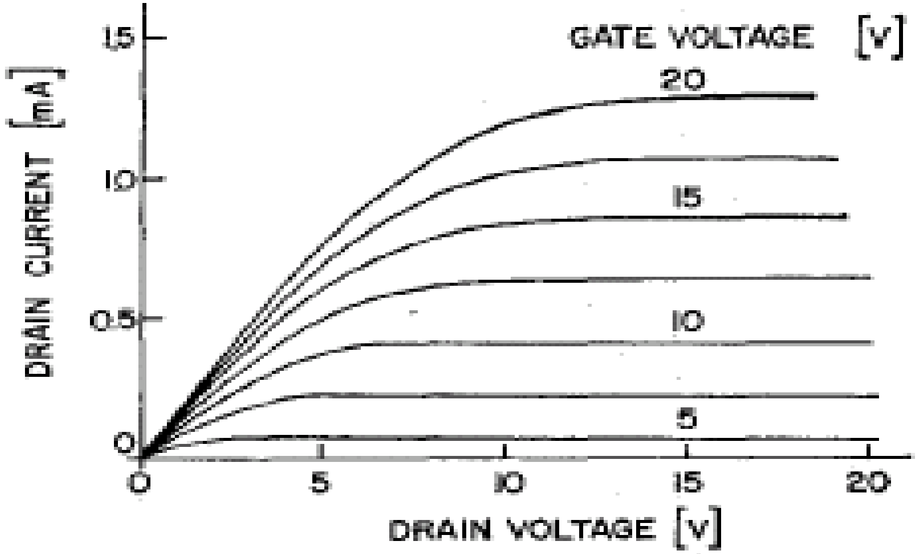
A. He will increase his interest for higher priced items.
B. He will increase his demand for higher priced items.
C. He will decrease his demand for lower priced substitutes.
D. He will increase his demand for lower priced substitutes.

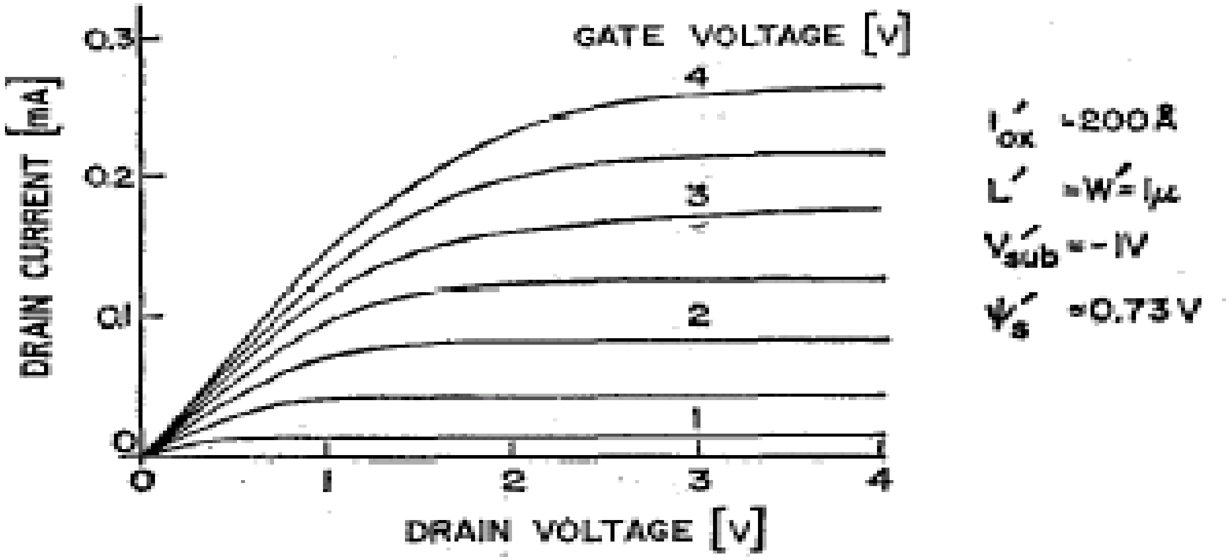
Taken from
http://www.ode.state.
chlearn/testing/samp
ocsci_sampletest_en



How did we end up with GPU computing anyway?

Dennard Scaling of MOS Devices



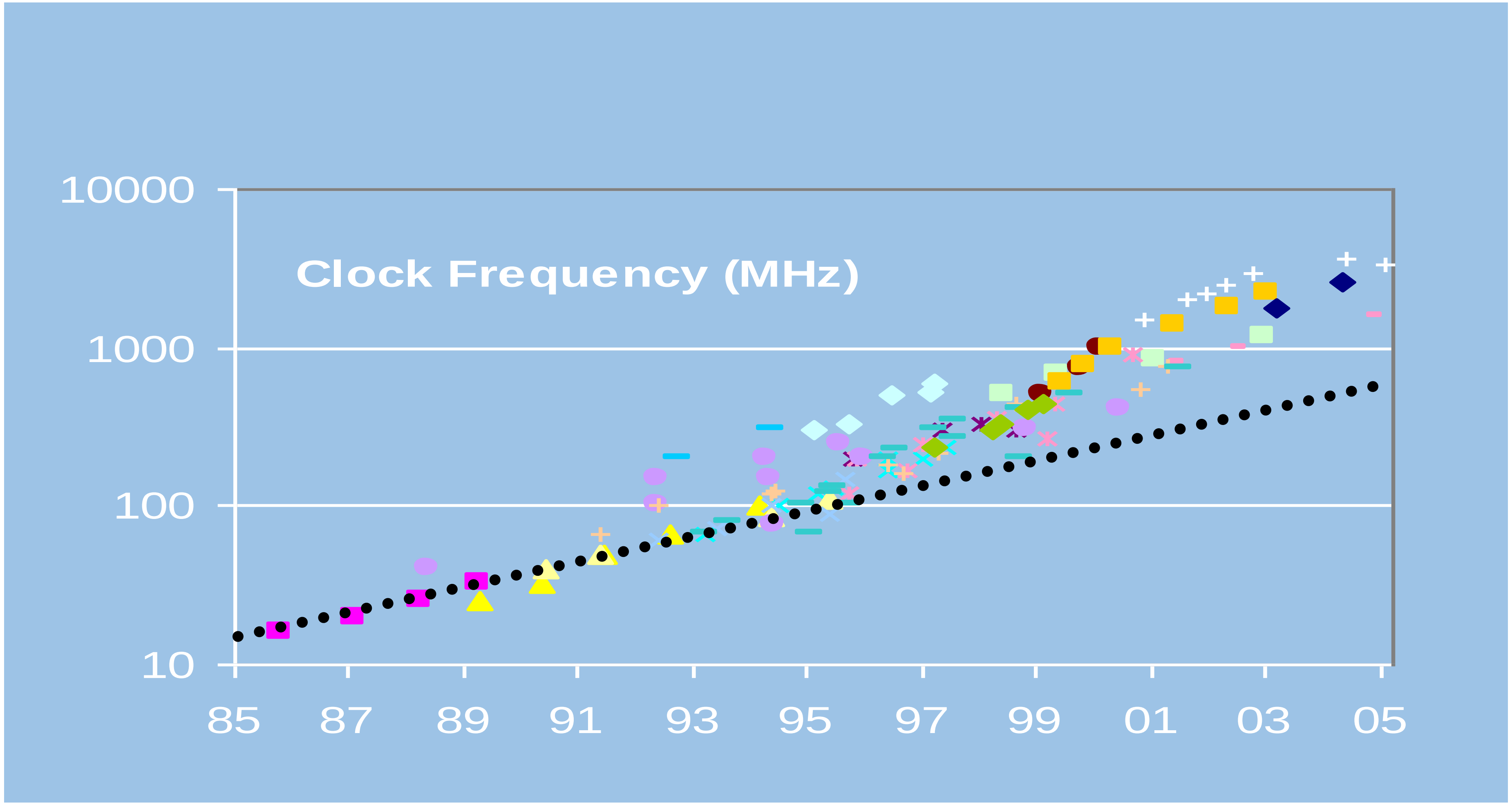


JSSC Oct **1974**, page 256

- In this ideal scaling, as $L \rightarrow \alpha * L$
  - $V_{DD} \rightarrow \alpha * V_{DD}$, $C \rightarrow \alpha * C$, $i \rightarrow \alpha * i$
  - Delay = CV_{DD}/I scales by α, so $f \rightarrow 1/\alpha$
  - Power for each transistor is $CV^2 * f$ and scales by α^2
    - keeping total power constant for same chip area

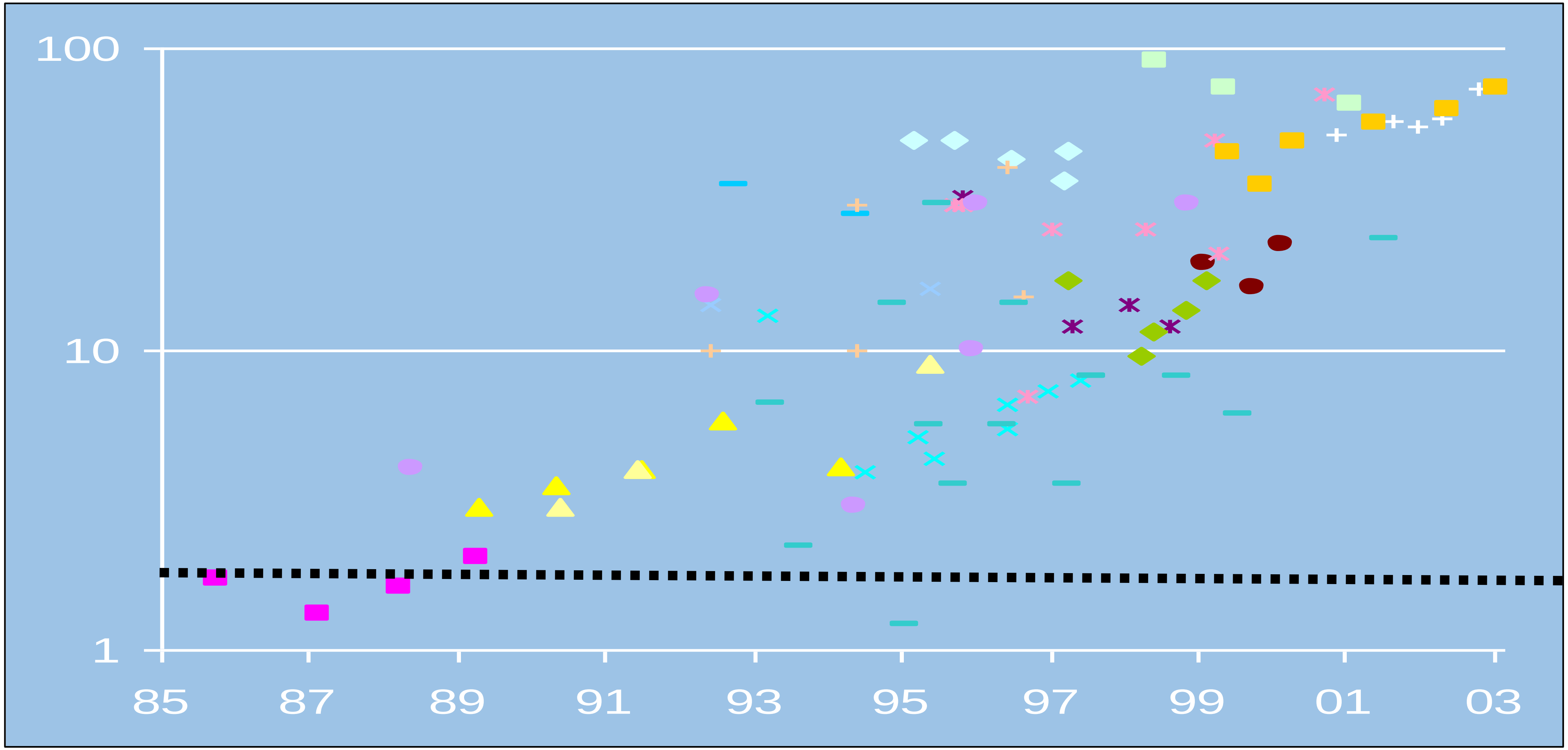
α has been 1.44 every 18 months

Frequency Scaled Too Fast 1993-2003



Total Processor Power Increased

(super-scaling of frequency and chip size)



Post-Dennard Pivoting

- Multiple cores with more moderate clock frequencies
- Heavy use of vector execution
- Employ both latency-oriented and throughput-oriented cores

Production Use Results CPU+GPU vs. CPU+CPU

	Application Description	Application Speedup
NAMD	100 million atom benchmark with Langevin dynamics and PME once every 4 steps, from launch to finish, all I/O included	1.8
Chroma	Lattice QCD parameters: grid size of 483 x 512 running at the physical values of the quark masses	2.4
QMCPACK	Full run Graphite 4x4x1 (256 electrons), QMC followed by VMC	2.7
ChaNGa	Collisionless N-body stellar dynamics with multipole expansion and hydrodynamics	2.1
AWP	Earthquake anelastic wave propagation with staggered-grid finite-difference and realistic plastic yielding	3.7-5.0

More Heterogeneity Is Coming

- Beyond traditional CPUs and GPUs
  - FPGAs (e.g., Microsoft FPGA cloud)
  - ASICs (e.g., Google's TPU)

- Beyond traditional DRAM
  - Stacked DRAM for more memory bandwidth
  - Non-volatile RAM for memory capacity
  - Near/in memory computing for reduced power used in data movement

Engineering high-efficiency software for heterogeneous computing

Performance-Portability: One Source for All

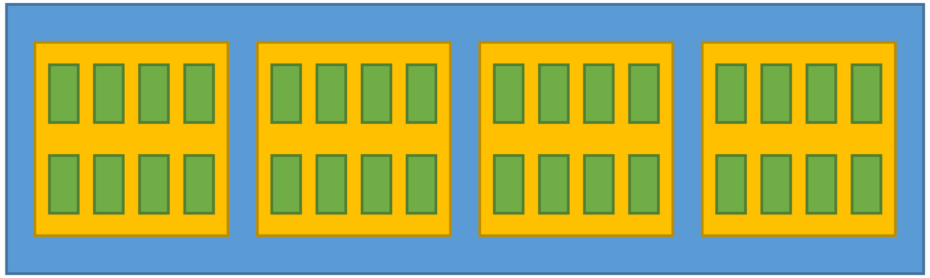
Challenges	Granularity of Parallelism	Levels of Hierarchy	Memory Characteristics	Resource Sizes	Micro-architecture
Solutions	Coarsening	Codelet Composition	Automatic Data Placement	Autotuning	Algorithmic Choice

Hierarchical Compute Organization of Devices

```
tile = (len + gridDim.x – 1)/gridDim.x;
sub_tile = (tile + blockDim.x – 1)/blockDim.x;
accum = 0
#pragma unroll
for(unsigned i = 0; i < sub_tile; ++i) {
   accum += in[blockIdx.x*tile
        + i*blockDim.x + threadIdx.x];
}
tmp[threadIdx.x] = accum;
__syncthreads();
for(unsigned s=1; s<blockDim.x; s *= 2) {
    if(id >= s)
        tmp[threadIdx.x] +=
            tmp[threadIdx.x - s];
    __syncthreads();
}
partial[blockIdx.x] = tmp[blockDim.x-1];
return; // Launch new kernel to sum up partial
```

GPU

1. Grid
2. Block
3. Warp
4. Thread
5. Instruction-level Parallelism

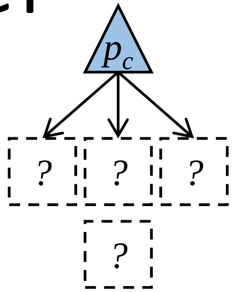


Tangram: Codelet-based Programming Model

c_a

```
__codelet
int sum(const Array<1,int> in) {
  unsigned len = in.size();
  int accum = 0;
  for(unsigned i=0; i < len; ++i) {
    accum += in[i];
  }
  return accum;
}
```

(a) Atomic autonomous codelet



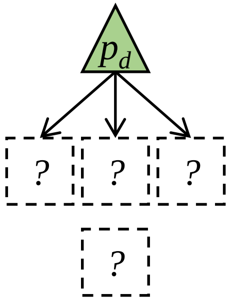

```
__codelet  __tag(asso_tiled)
int sum(const Array<1,int> in) {
  __tunable unsigned p;
  unsigned len = in.size();
  unsigned tile = (len+p-1)/p;
  return sum( map( sum, partition(in,
      p,sequence(0,tile,len),sequence(1),sequence(tile,tile,len+1))));
}
```

(c) Compound codelet using adjacent tiling

c_b

```
__codelet __coop __tag(kog)
int sum(const Array<1,int> in) {
  __shared int tmp[coopDim()];
  unsigned len = in.size();
  unsigned id = coopIdx();
  tmp[id] = (id < len)? in[id] : 0;
  for(unsigned s=1; s<coopDim(); s *= 2) {
    if(id >= s)
      tmp[id] += tmp[id - s];
  }
  return tmp[coopDim()-1];
}
```

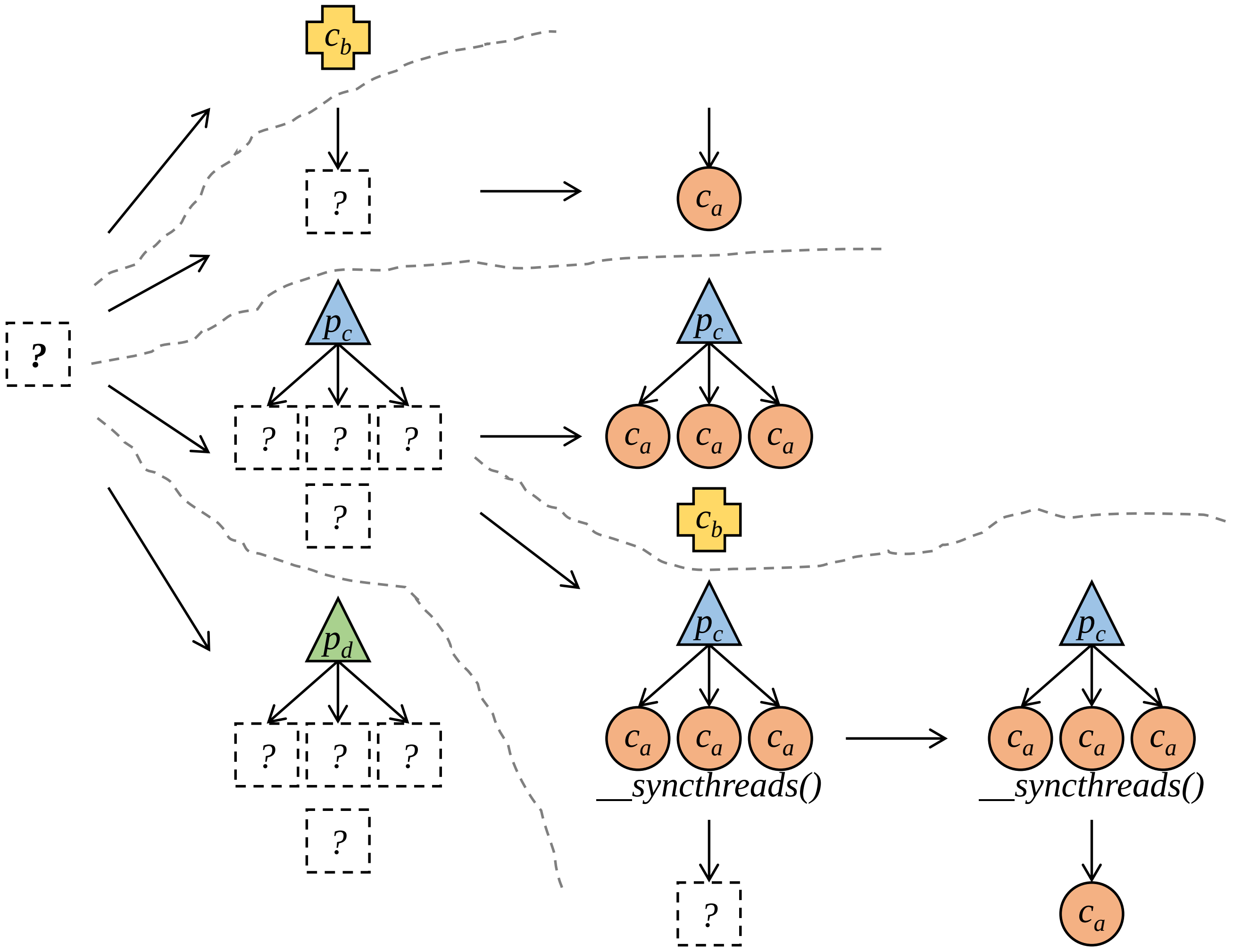
(b) Atomic cooperative codelet



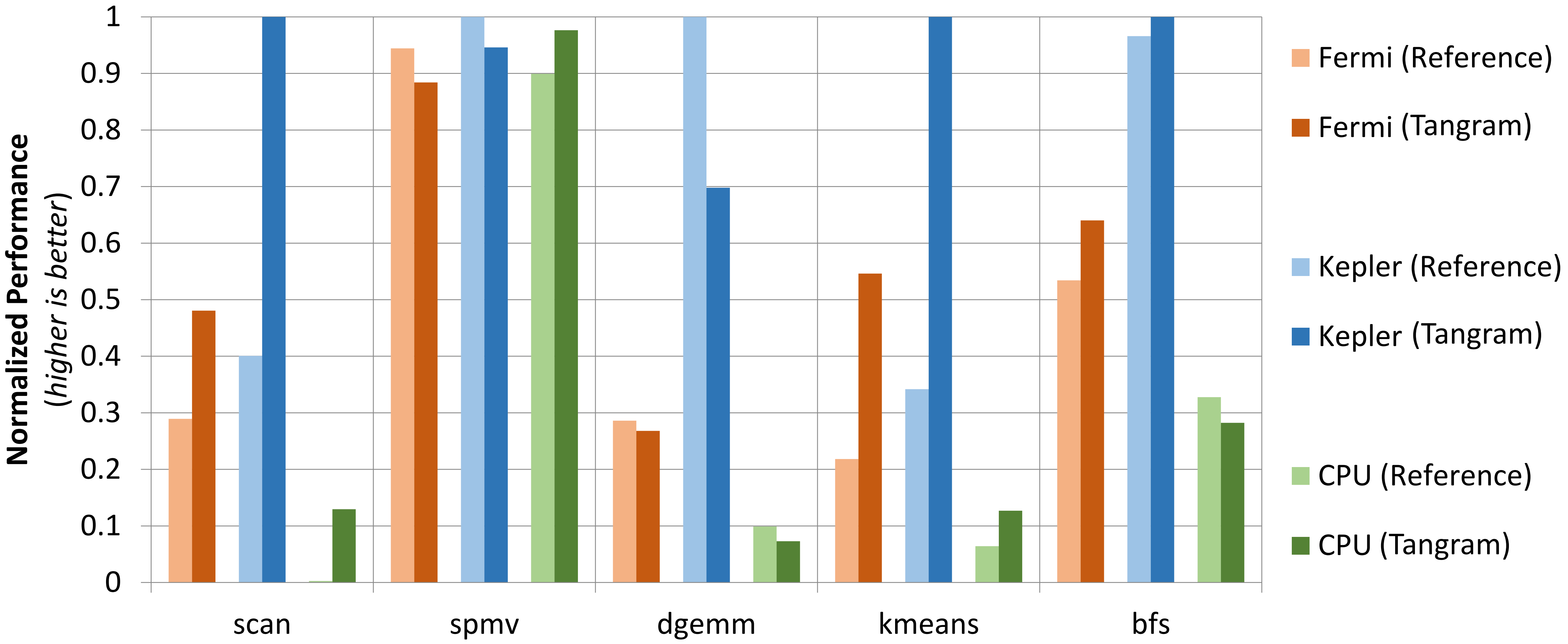

```
__codelet __tag(stride_tiled)
int sum(const Array<1,int> in) {
  __tunable unsigned p;
  unsigned len = in.size();
  unsigned tile = (len+p-1)/p;
  return sum( map( sum, partition(in,
      p,sequence(0,1,p),sequence(p),sequence((p-1)*tile,1,len+1))));
}
```

(d) Compound codelet using strided tiling

Tangram: Composition Example



Tangram Results



What is the stake?

- Scalable and portable software can empower many hardware generations

Scalable algorithms and libraries could be the best legacy we can leave behind from this era

Thank you!

Any more questions?