Unlocking Biologically-Inspired Computer Vision: a High-Throughput Approach

Nicolas Pinto, David Cox and James DiCarlo

NVIDIA GTC | October, 2009

The Rowland Institute at Harvard
HARVARD UNIVERSITY

Unlockin… …ed
Comput…
a High-T… …n

…tute at Harvard
…SITY

Unlocking Biologically-Inspired Computer Vision: a High-Throughput Approach

=

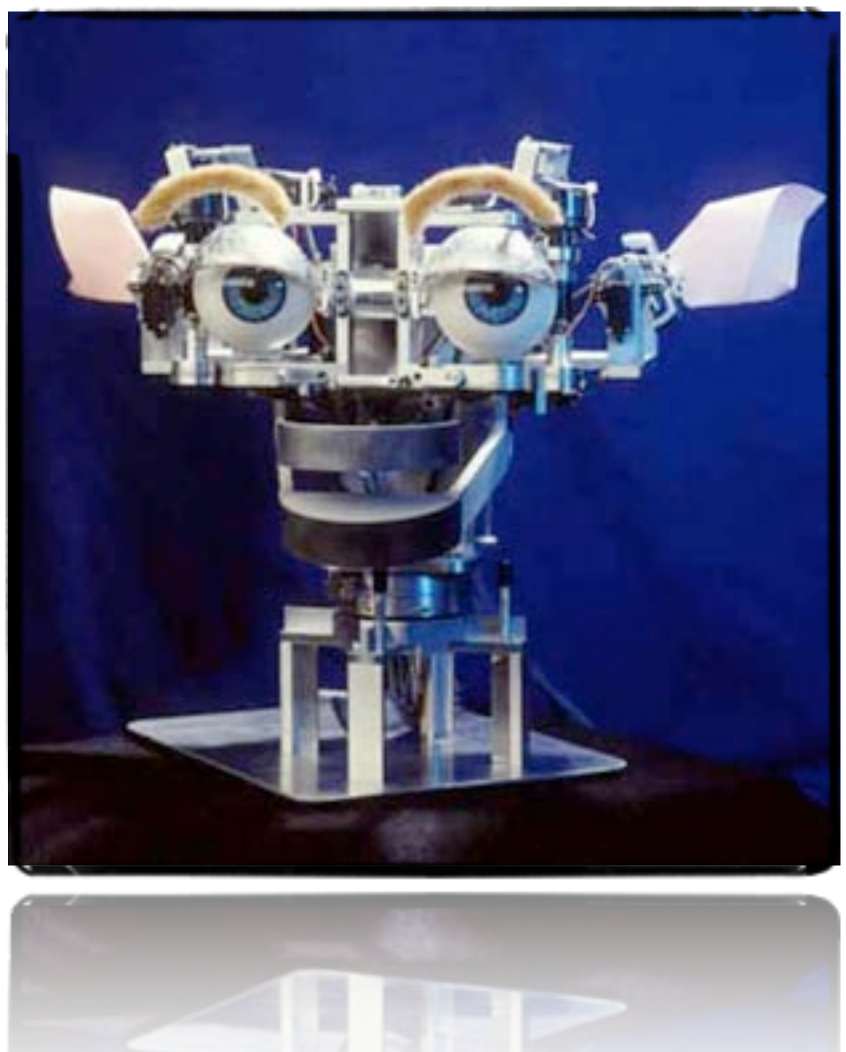
BRAIN

(NEUROSCIENCES)

Unlocking Biologically-Inspired

Computer Vision:

a High-Throughput Approach



= A.I.

Unlocking Biologically-Inspired Computer Vision: a High-Throughput Approach

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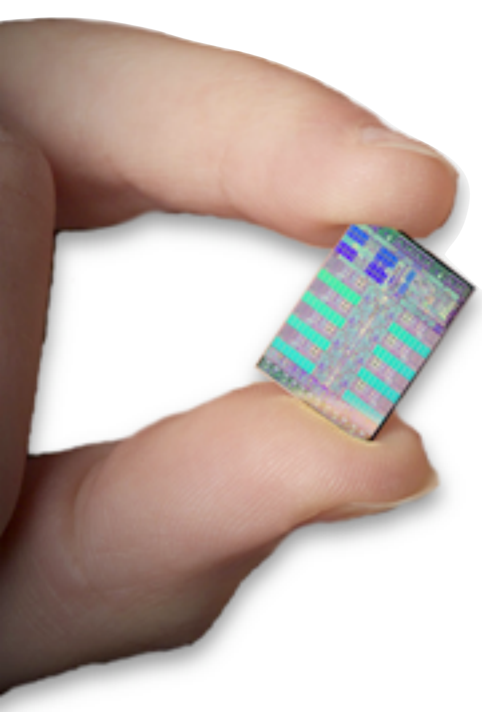
GPU



Quote to remember...

Friend: **So, what are you studying for your PhD?**

Me: **I study biological and artificial vision.**

Friend: **What?!? But vision is super easy!**

The Problem:
Visual Object Recognition

The Problem:
Visual Object Recognition

The Problem:
Visual Object Recognition

- *Fast*

The Problem:
Visual Object Recognition

- *Fast*
- *Accurate*

The Problem:
Visual Object Recognition

- *Fast*
- *Accurate*
- *Tolerant to variation*

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- *Fast*
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- *Effortless*

The Problem:
Visual Object Recognition

- *Fast*
- *Accurate*
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- *Effortless*
- *Critical to survival*

The Problem:
Visual Object Recognition

- *Fast*
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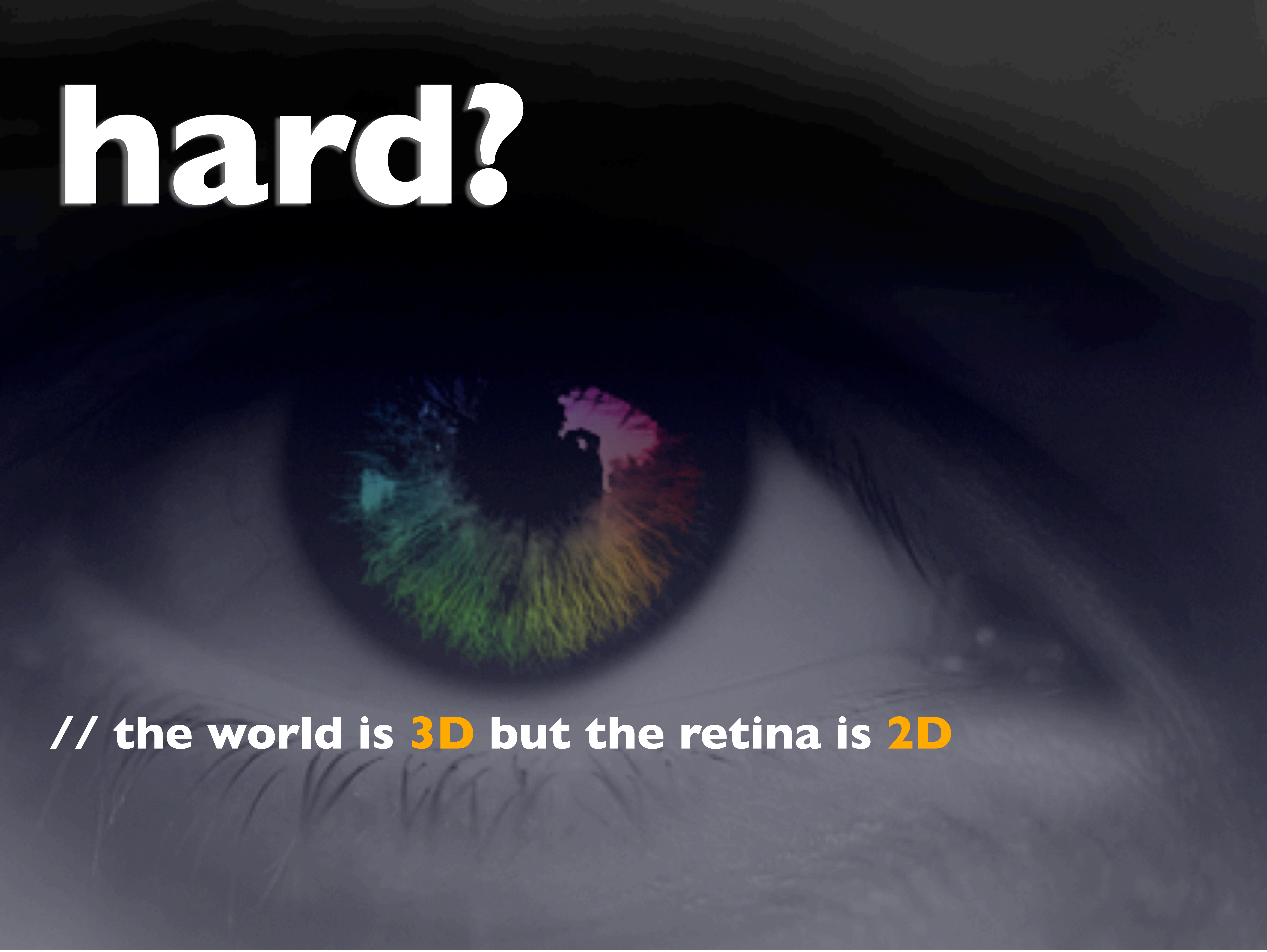
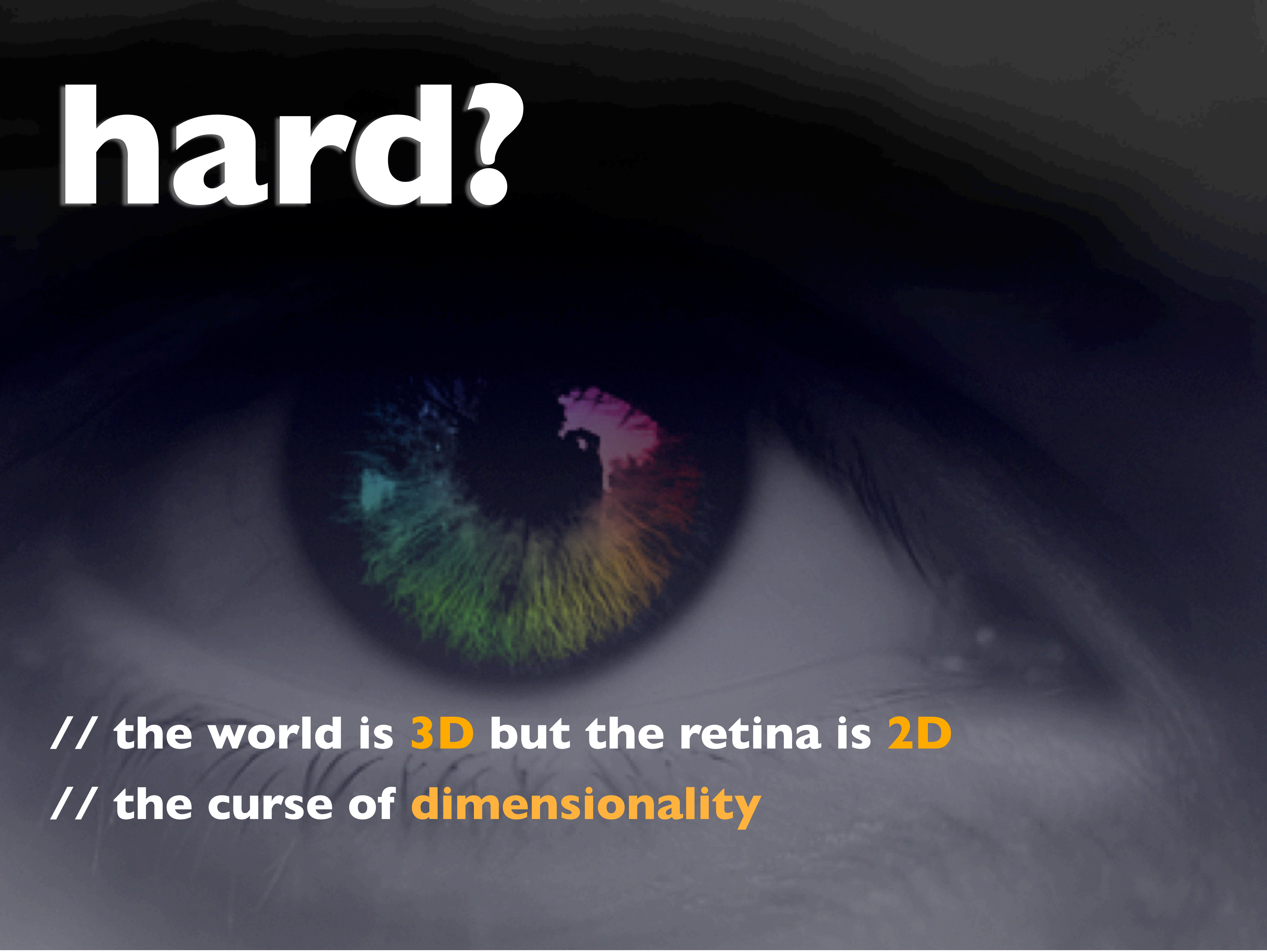
(for primates)


hard?

hard?



// the world is **3D** but the retina is **2D**


hard?
// the world is 3D but the retina is 2D
// the curse of dimensionality


hard?
// the world is 3D but the retina is 2D
// the curse of dimensionality
// considerable image variation


image variation!
do you recognize me ?
VOX

image variation!

do you recognize me ?

image variation!

do you recognize me ?

image variation!

do you recognize me ?

image variation!

do you recognize me ?

the brain!

~50% of that is for vision!

you learned it...

Need for speed

Hardware

Software

Science

The Approach:
Reverse Engineering the Brain

REVERSE

Study
Natural System

The Approach:
Reverse Engineering the Brain

REVERSE

Study
Natural System

FORWARD

Build
Artificial System

The Approach:
Reverse Engineering the Brain

REVERSE

FORWARD

Study
Natural System

Build
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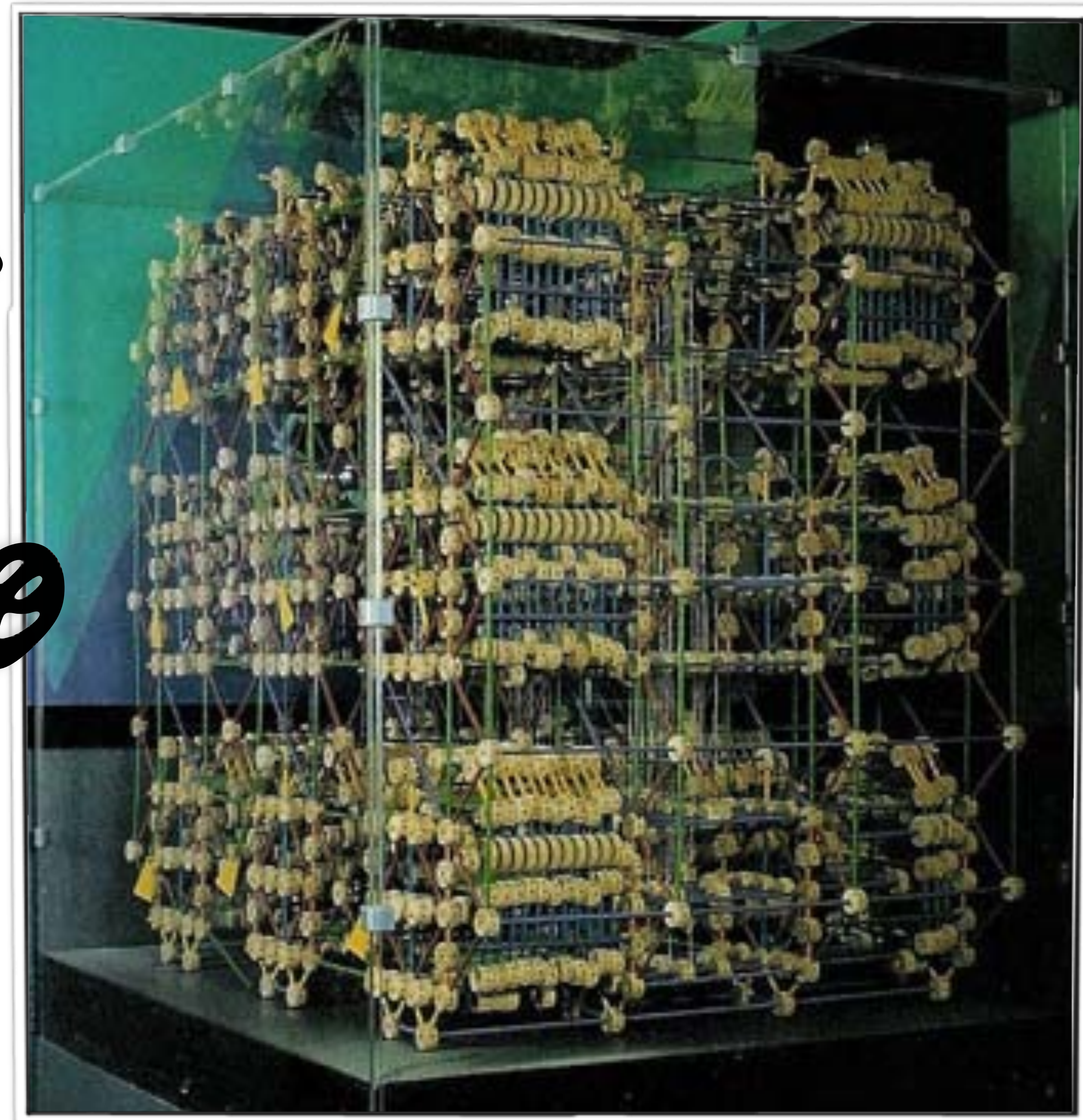
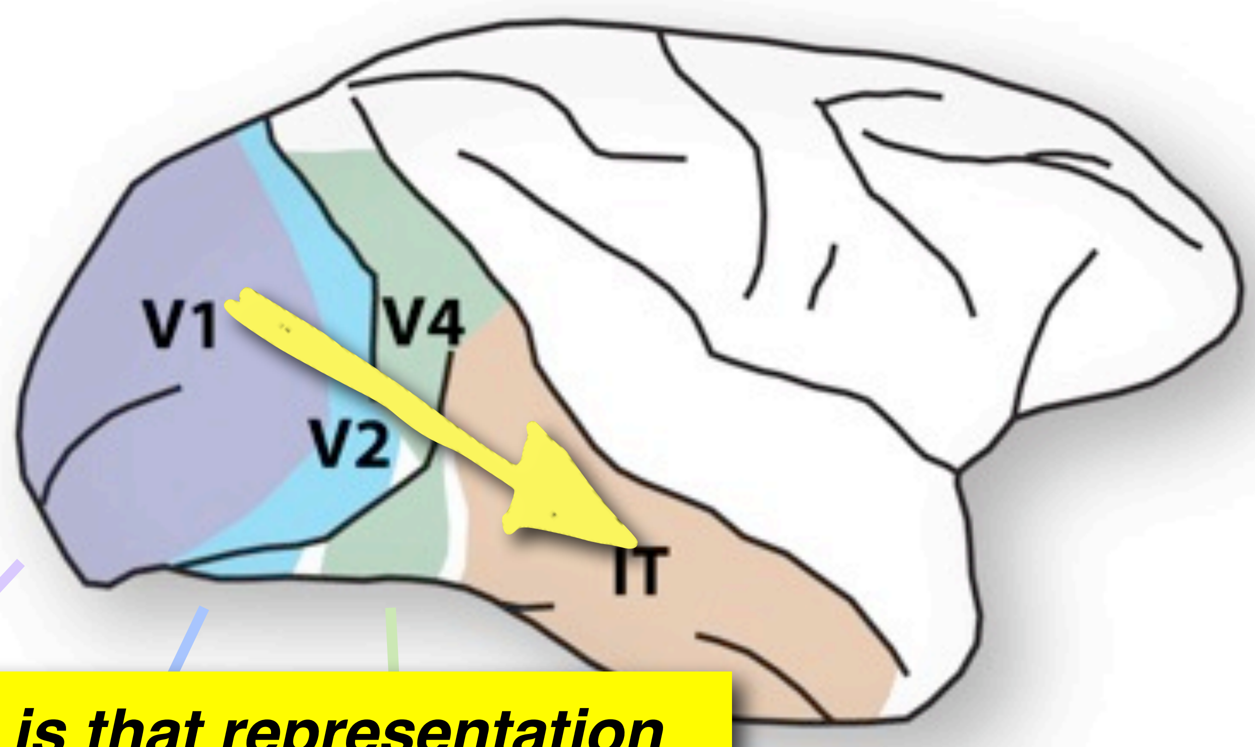
Reverse Engineering ...

What is this doing?



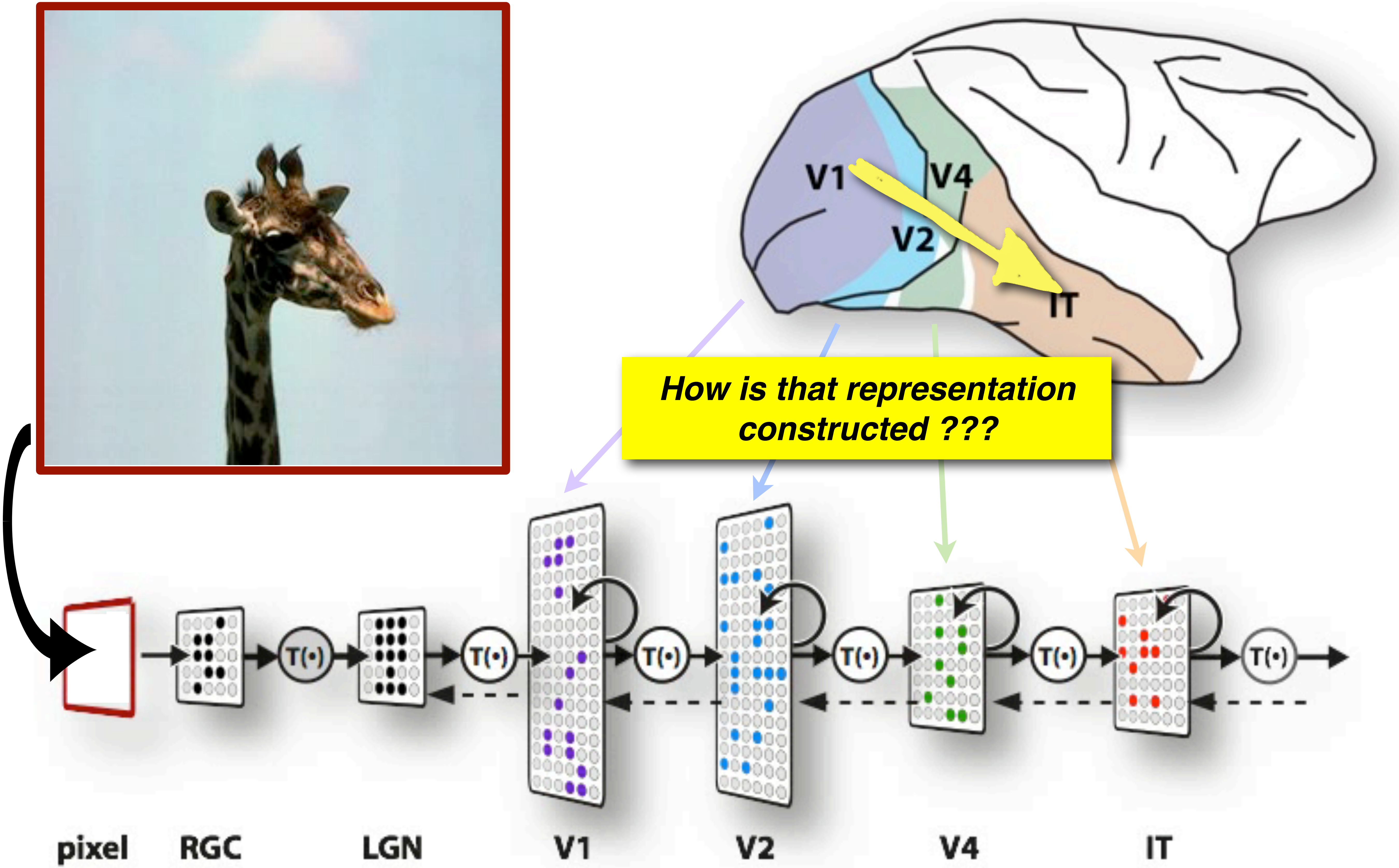
Reverse Engineering **the Brain!**

The Ventral Visual Stream



How is that representation constructed ???

The Ventral Visual Stream



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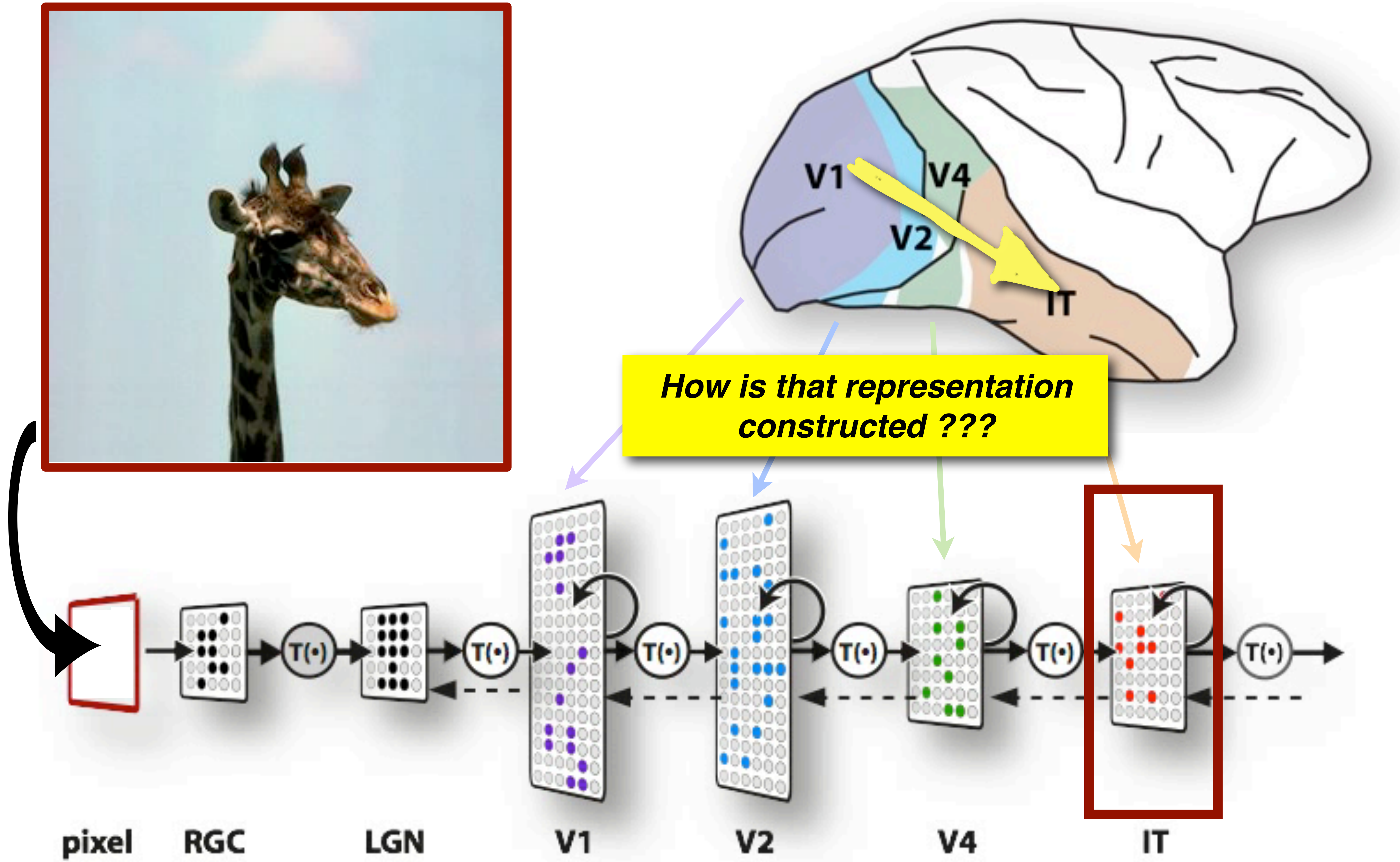
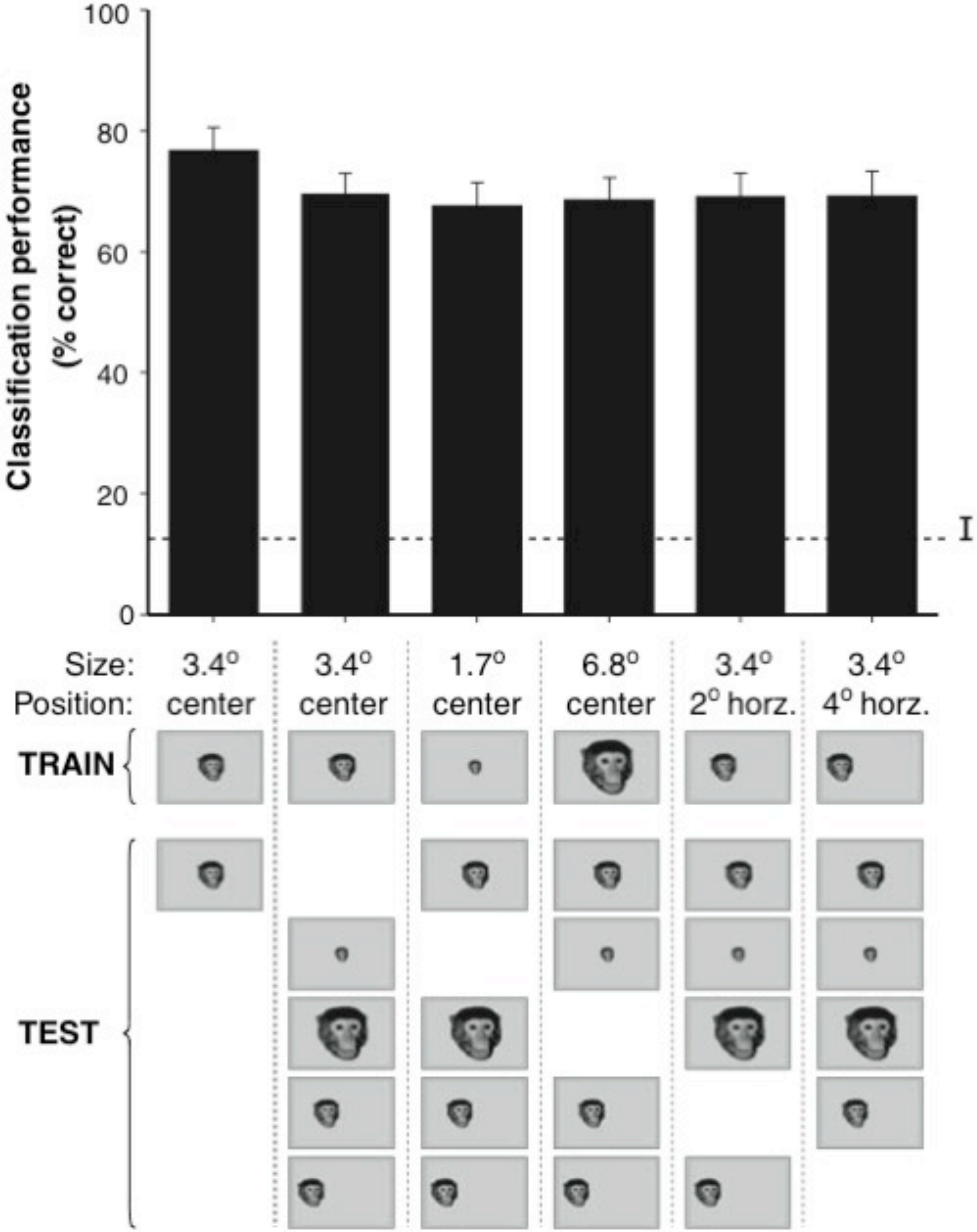
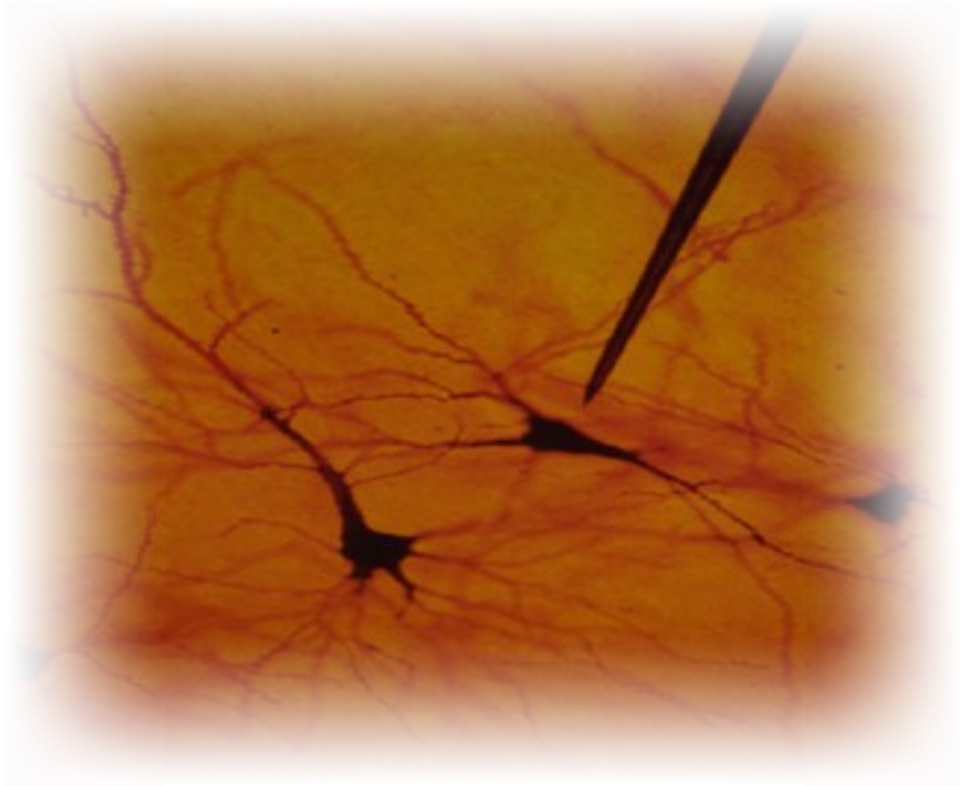


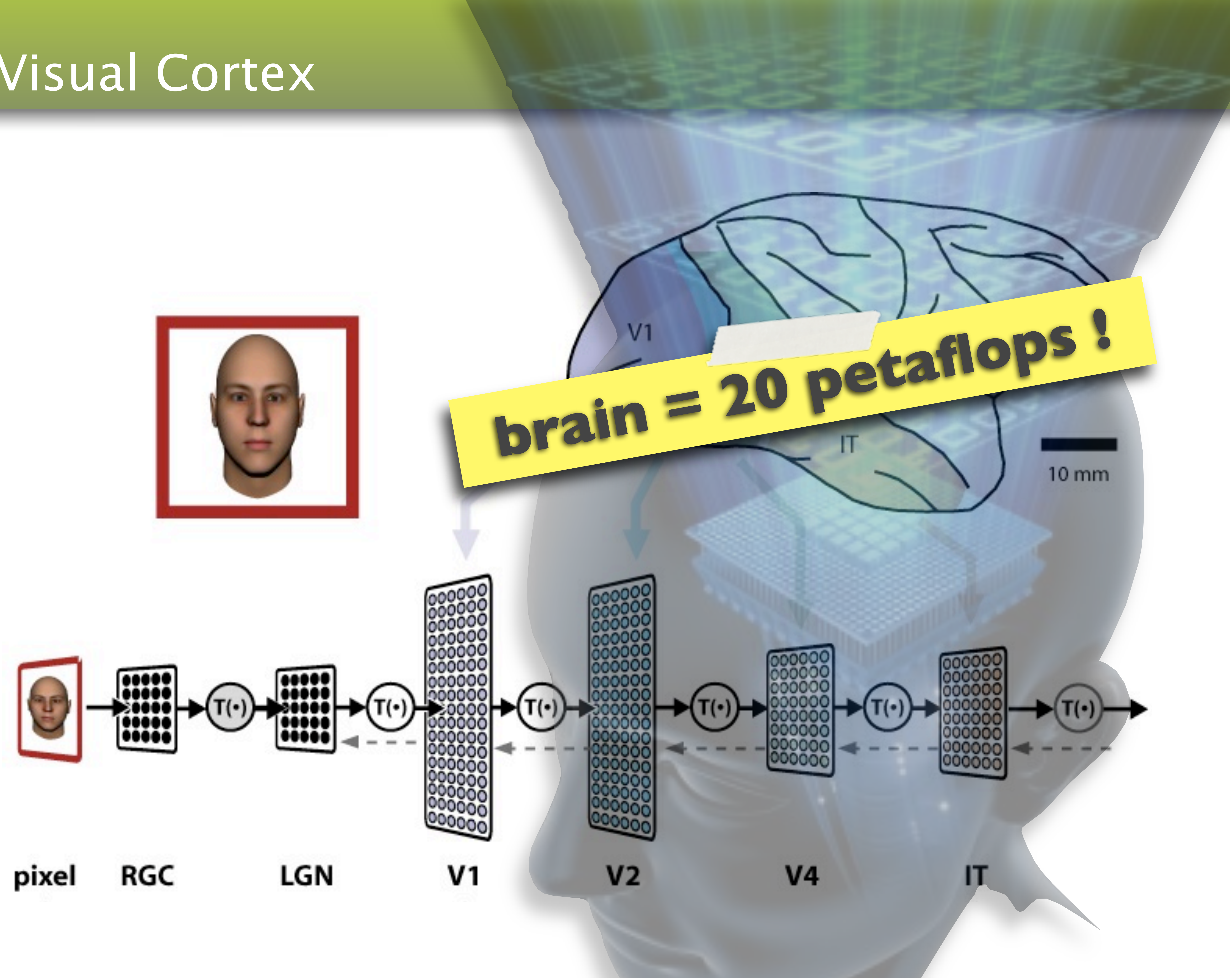
IT Cortex can do object recognition





Hung, Kreiman*, Poggio and DiCarlo,* ***Science*** *(2005)*

Visual Cortex



The need for **speed**

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- **billions** of neurons and synapses

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- **large-scale** natural evolution (“high-throughput screening” of neural architectures)

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- **hours** of unsupervised learning experience

The need for **speed**

- **billions** of neurons and synapses
- **large-scale** natural evolution (“high-throughput screening” of neural architectures)
- **hours** of unsupervised learning experience
- faithful reproduction of other models (i.e. blend **many highly tuned** techniques)

Wanna Play with The Big Guys?

But it's too expensive !!!

Take a chance.

Our strategy

Our strategy

Capitalizing on non-scientific high-tech markets and their $billions of R&D...

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– **Gaming:** GPUs, PlayStation 3 (CellBE)

Our strategy

Capitalizing on non-scientific high-tech markets and their $billions of R&D...

- **Gaming:** GPUs, PlayStation 3 (CellBE)
- **Web 2.0:** Cloud Computing (Amazon, Google)

Need for speed

Hardware

Software

Science

GPUs (since 2006)

7800 GTX (2006)	Monster16GPU (2008)	Tesla Cluster (2009)
OpenGL/Cg	*CUDA*	*CUDA/OpenCL*
C++/Python	*Python*	*Python*

Build your own!

Our 16-GPU Monster-Class Supercomputer

the world's most compact (18"x18"x18") and inexpensive ($3000) supercomputer

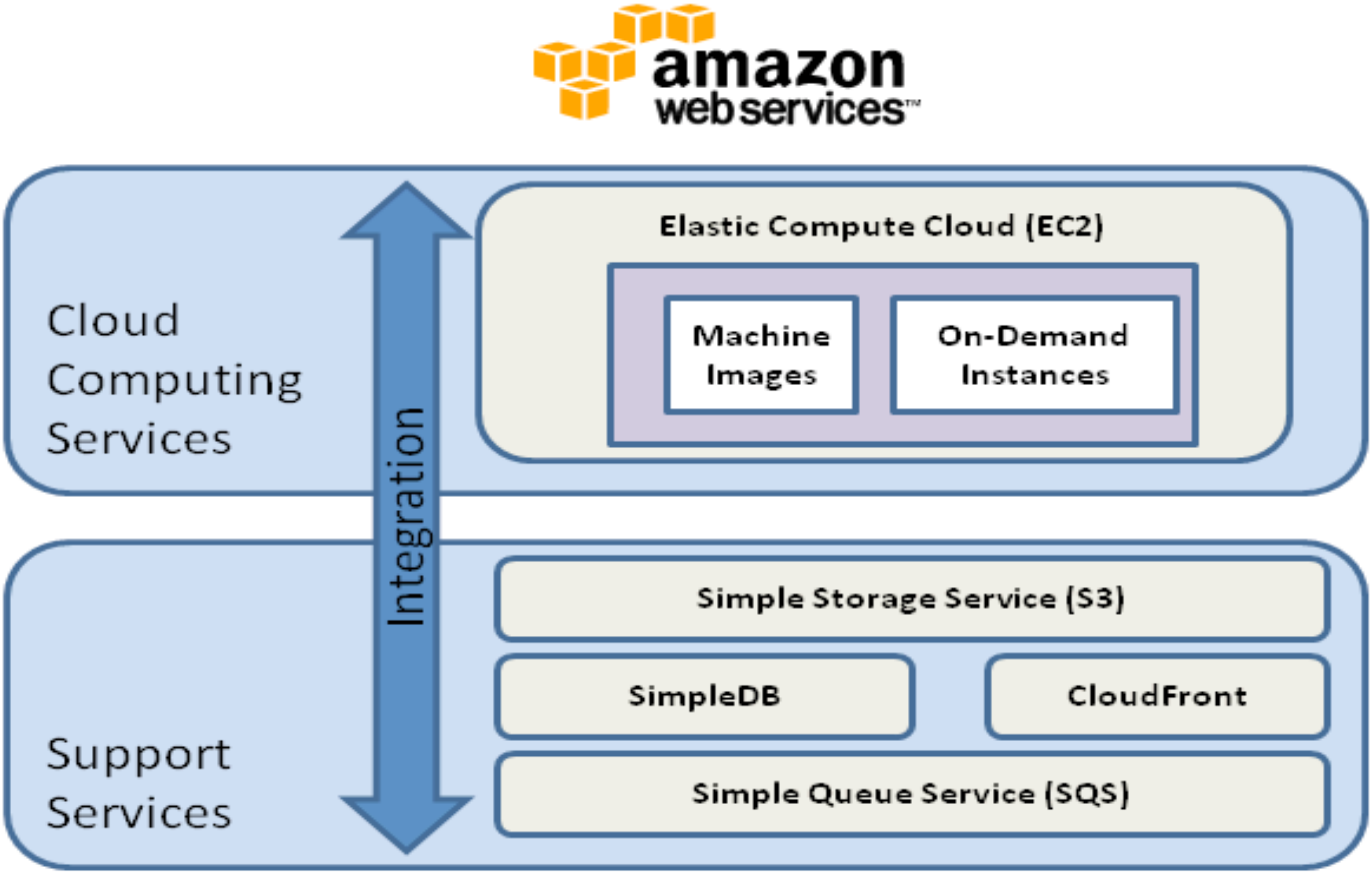
Cell Broadband Engine (since 2007)

Teraflop Playstation3 clusters:

DiCarlo Lab / MIT

Cox Lab / Harvard

Amazon Cloud Computing (since 2008)



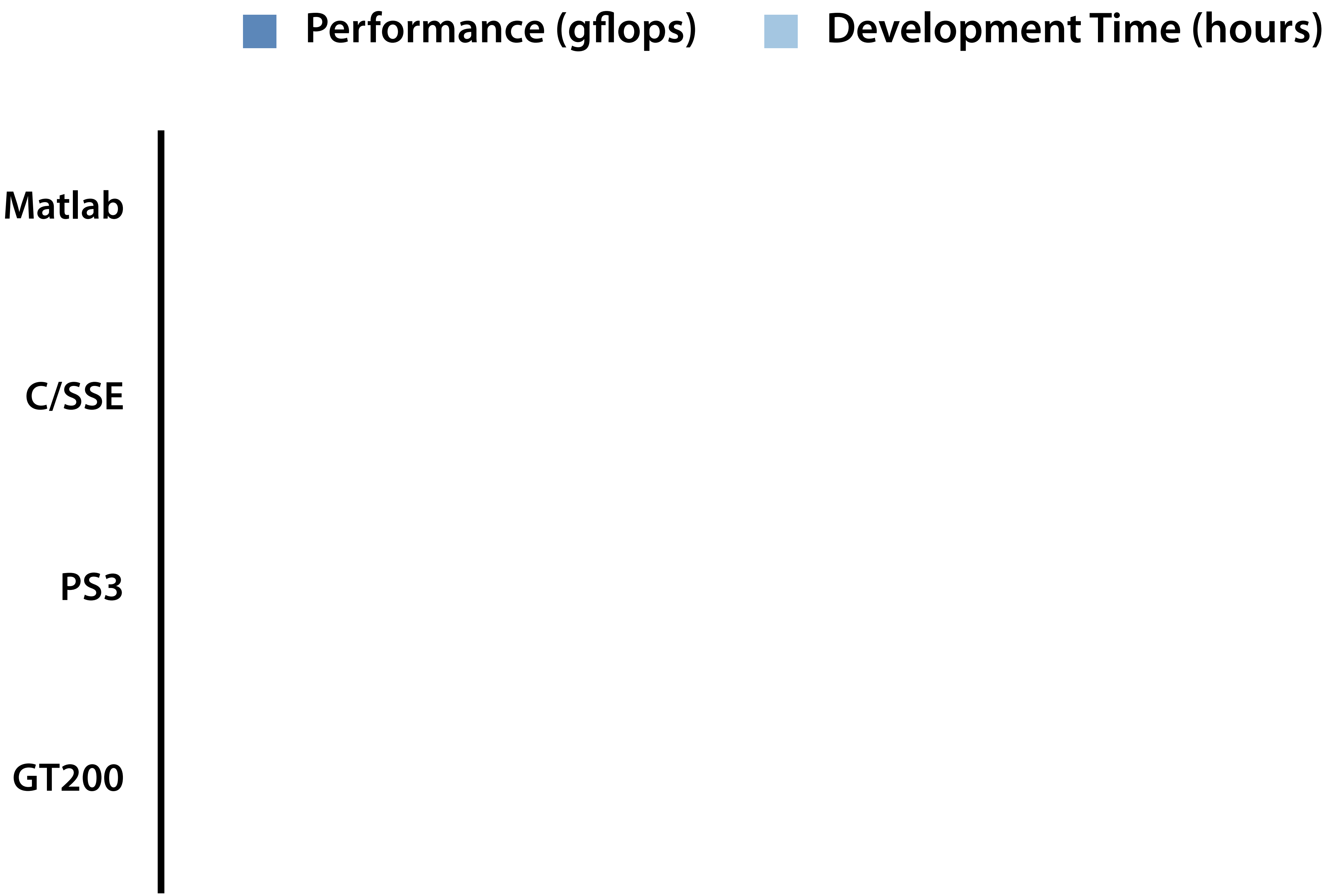
Some numbers...

3D Filterbank Convolution

Performance (gflops) | Development Time (hours)

Some numbers...

3D Filterbank Convolution



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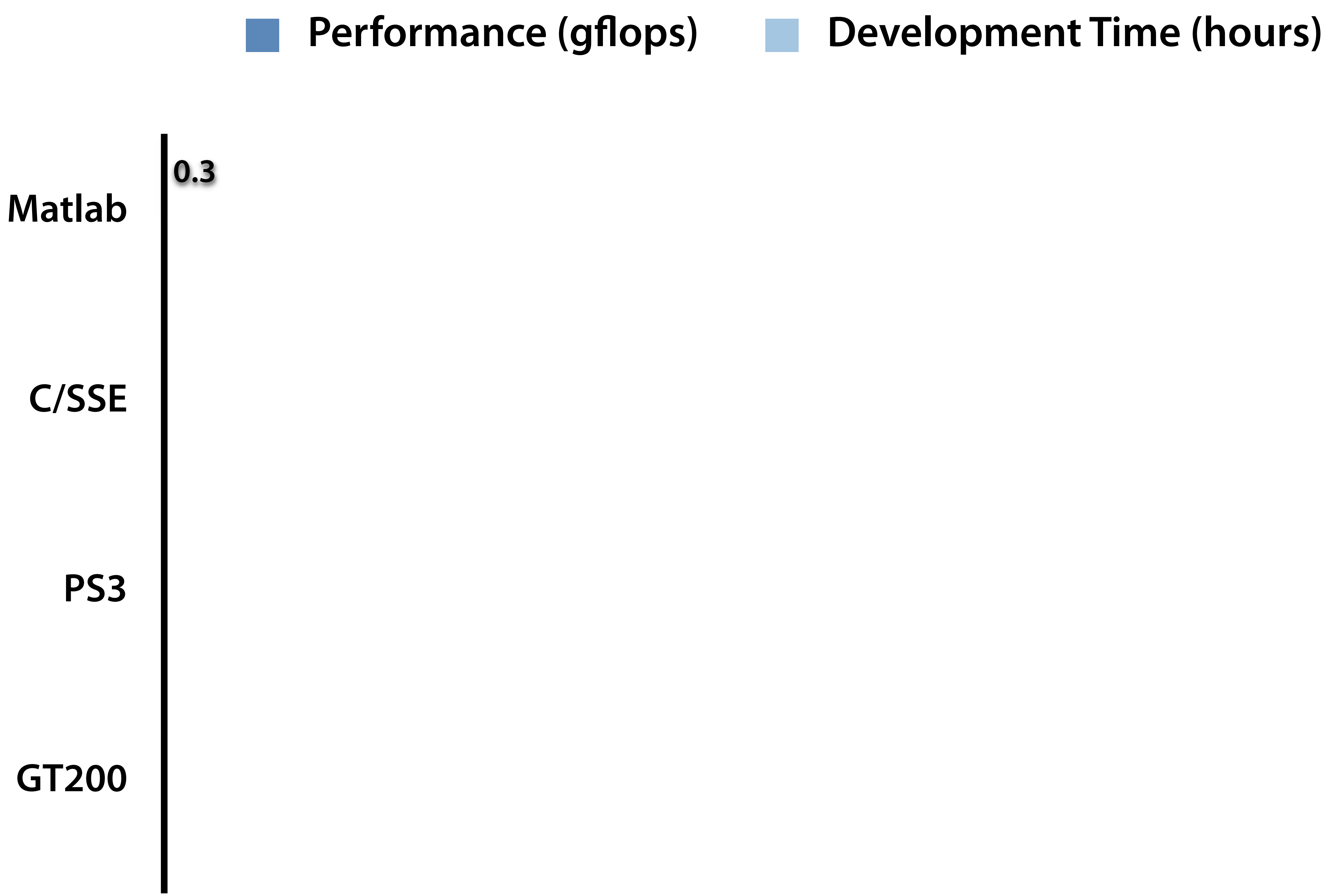

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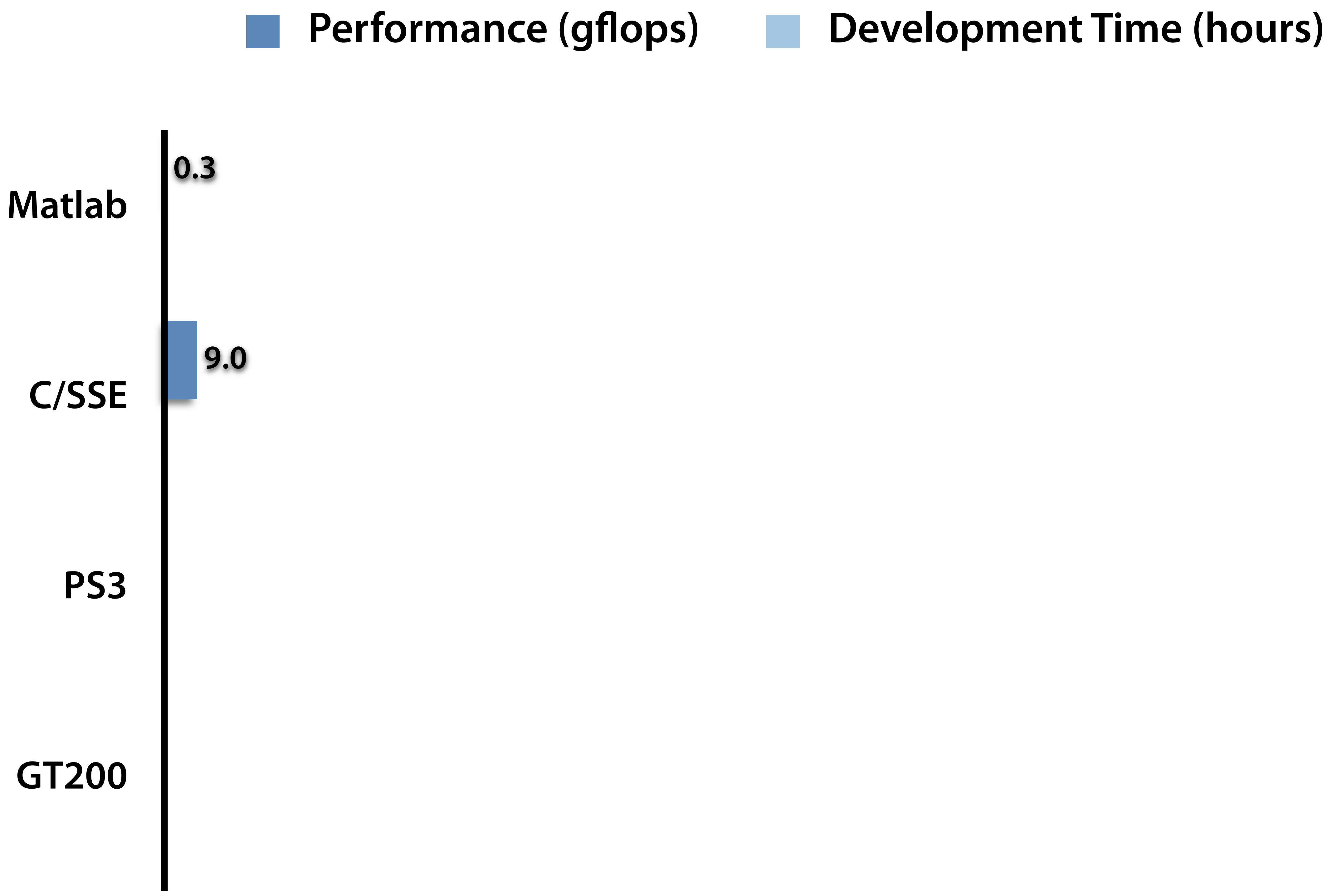

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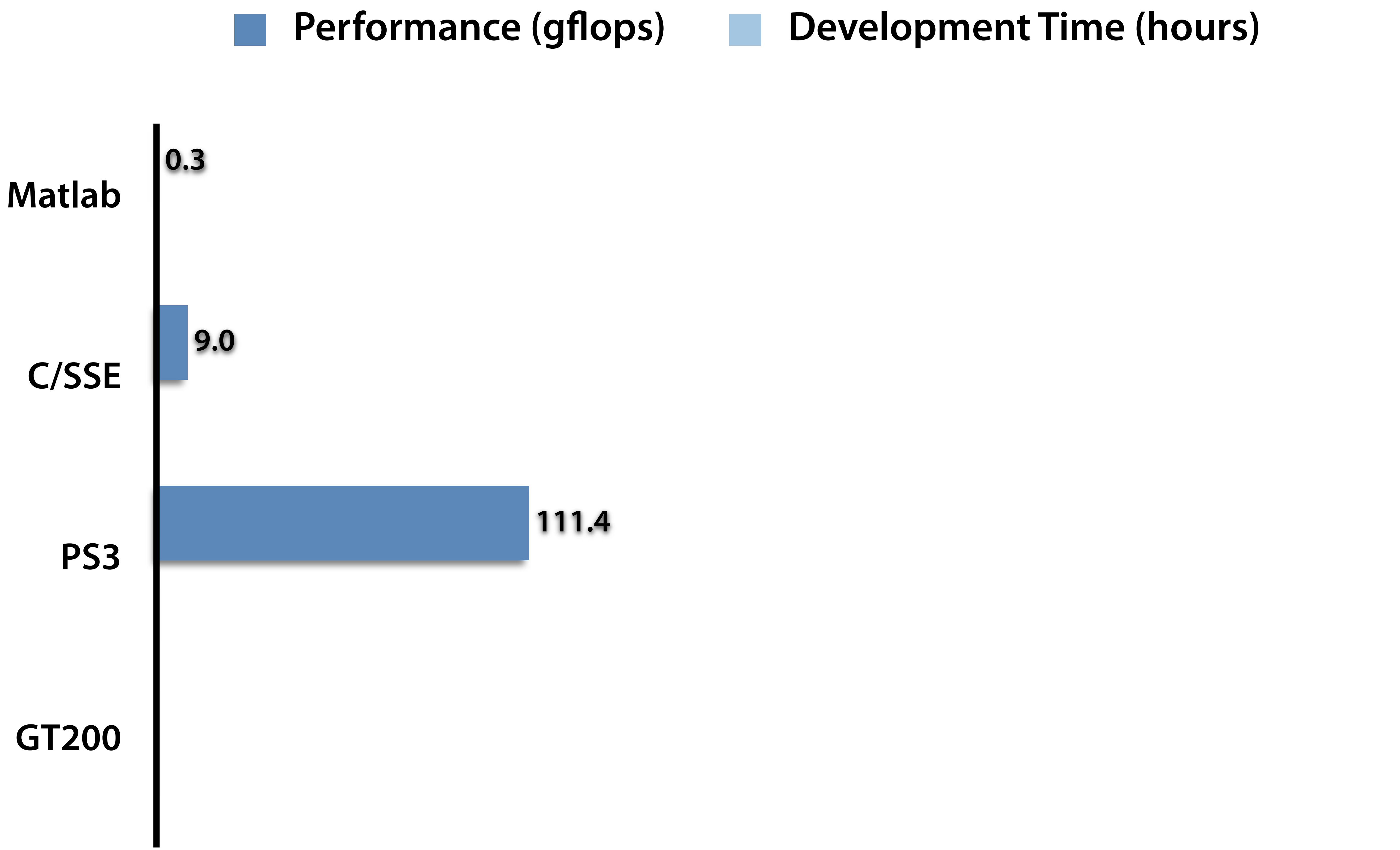

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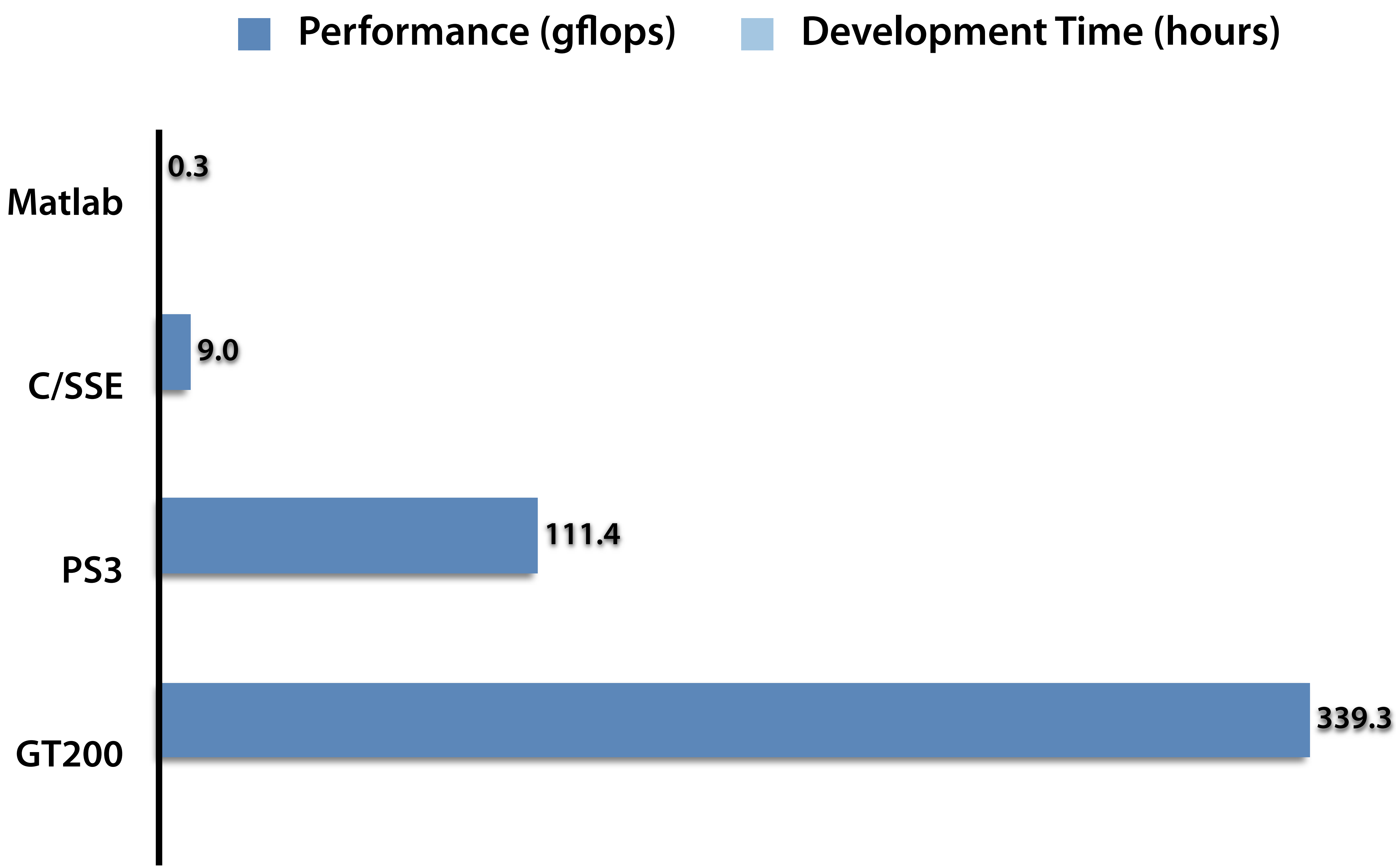

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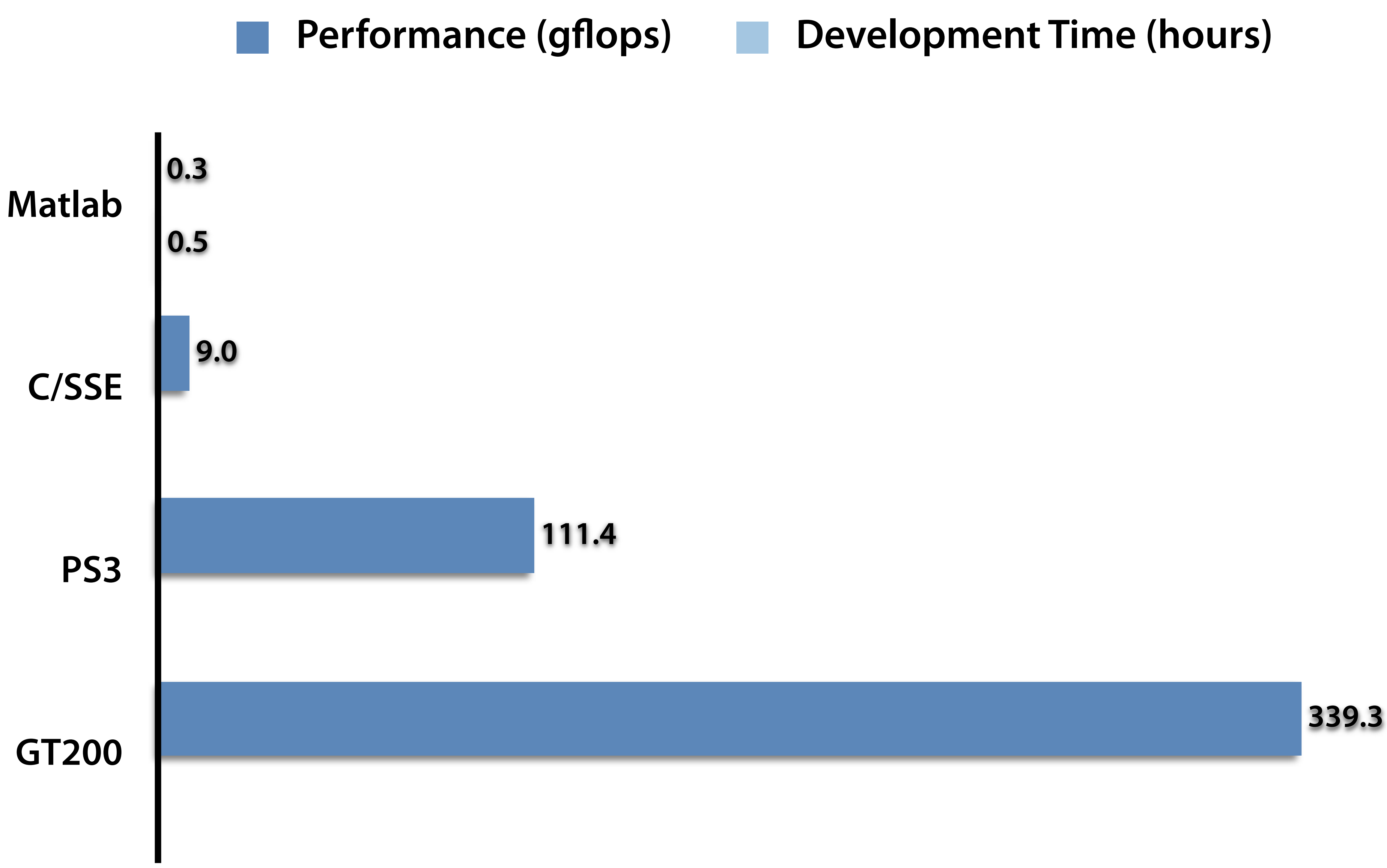

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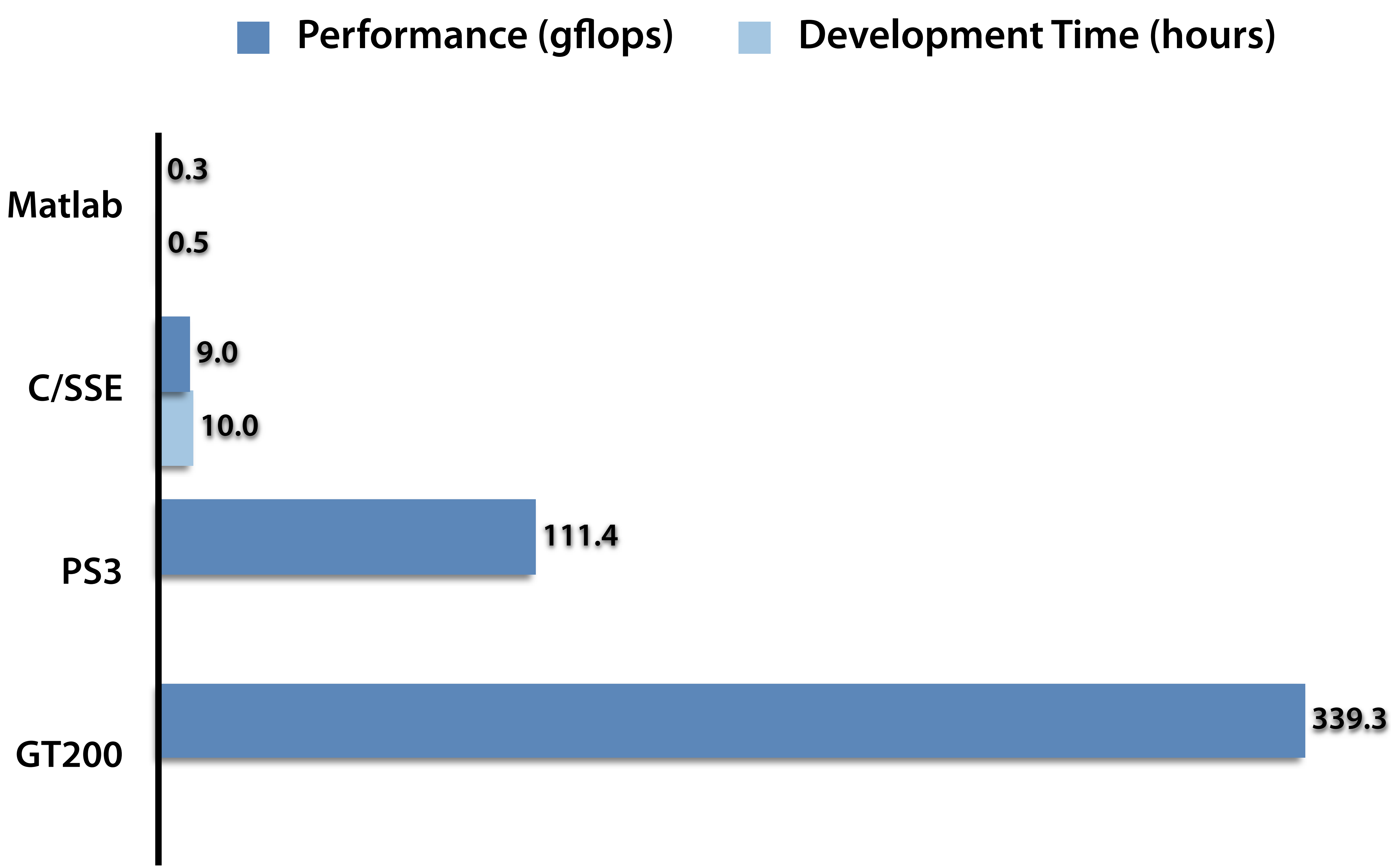

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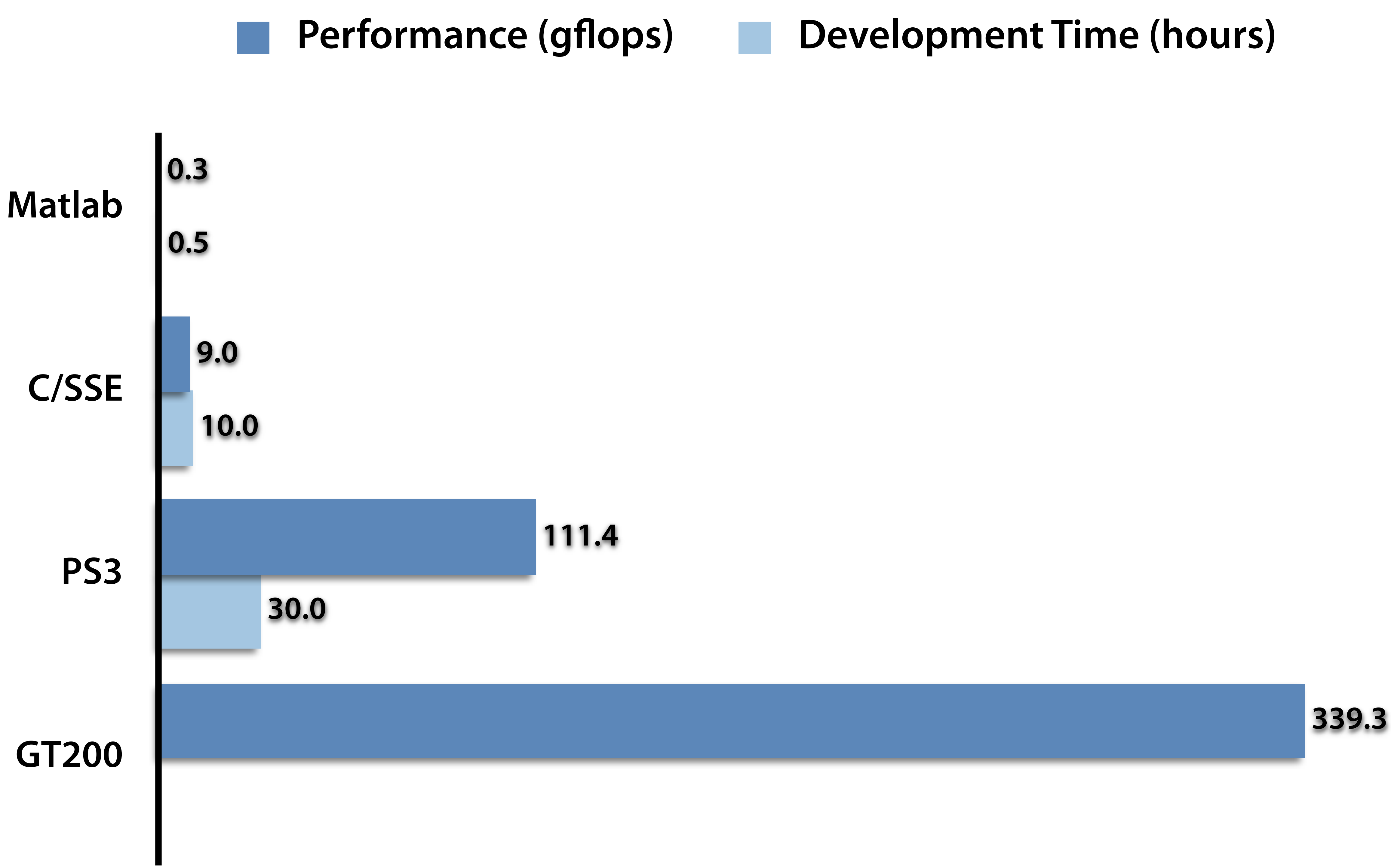

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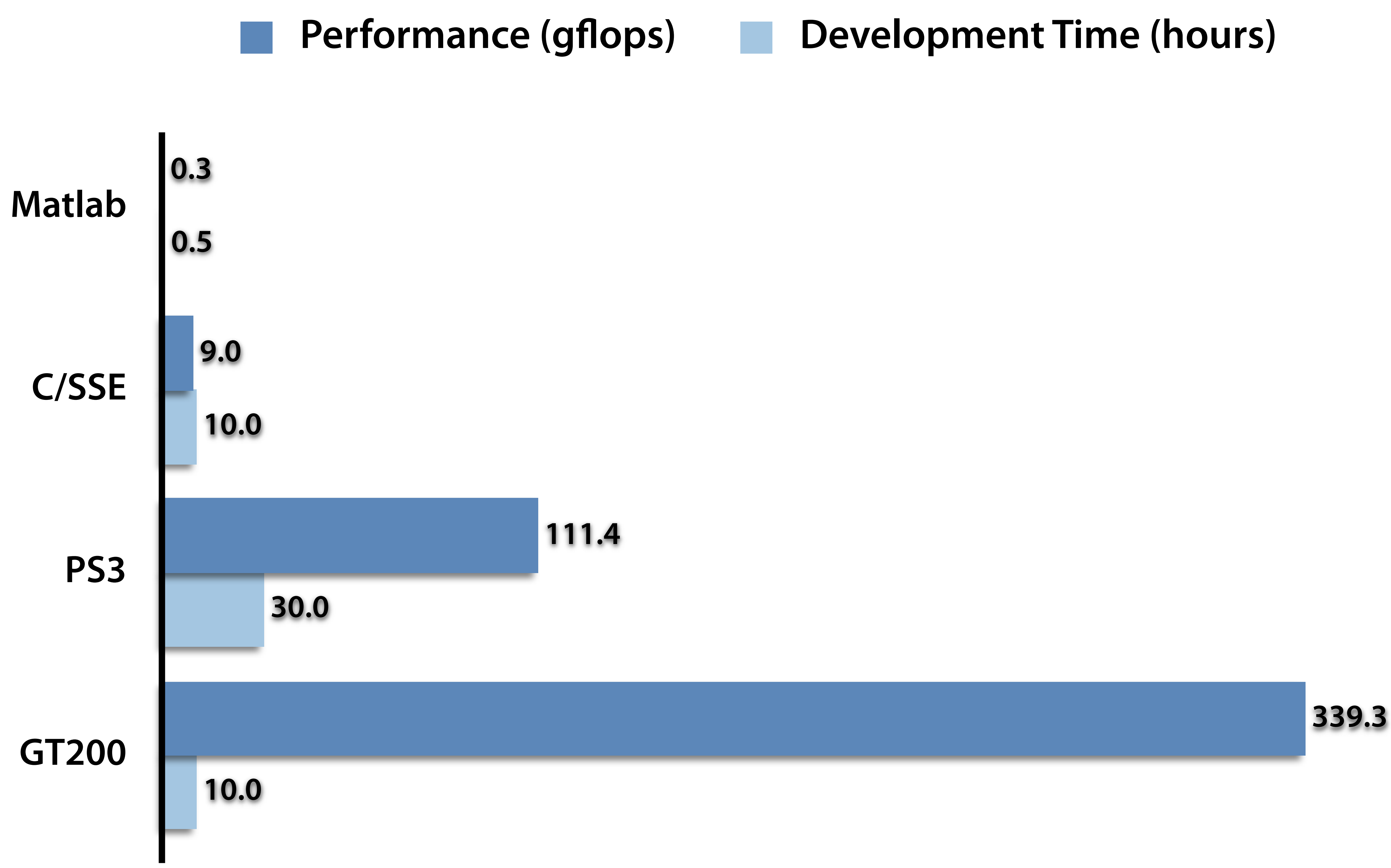
3D Filterbank Convolution



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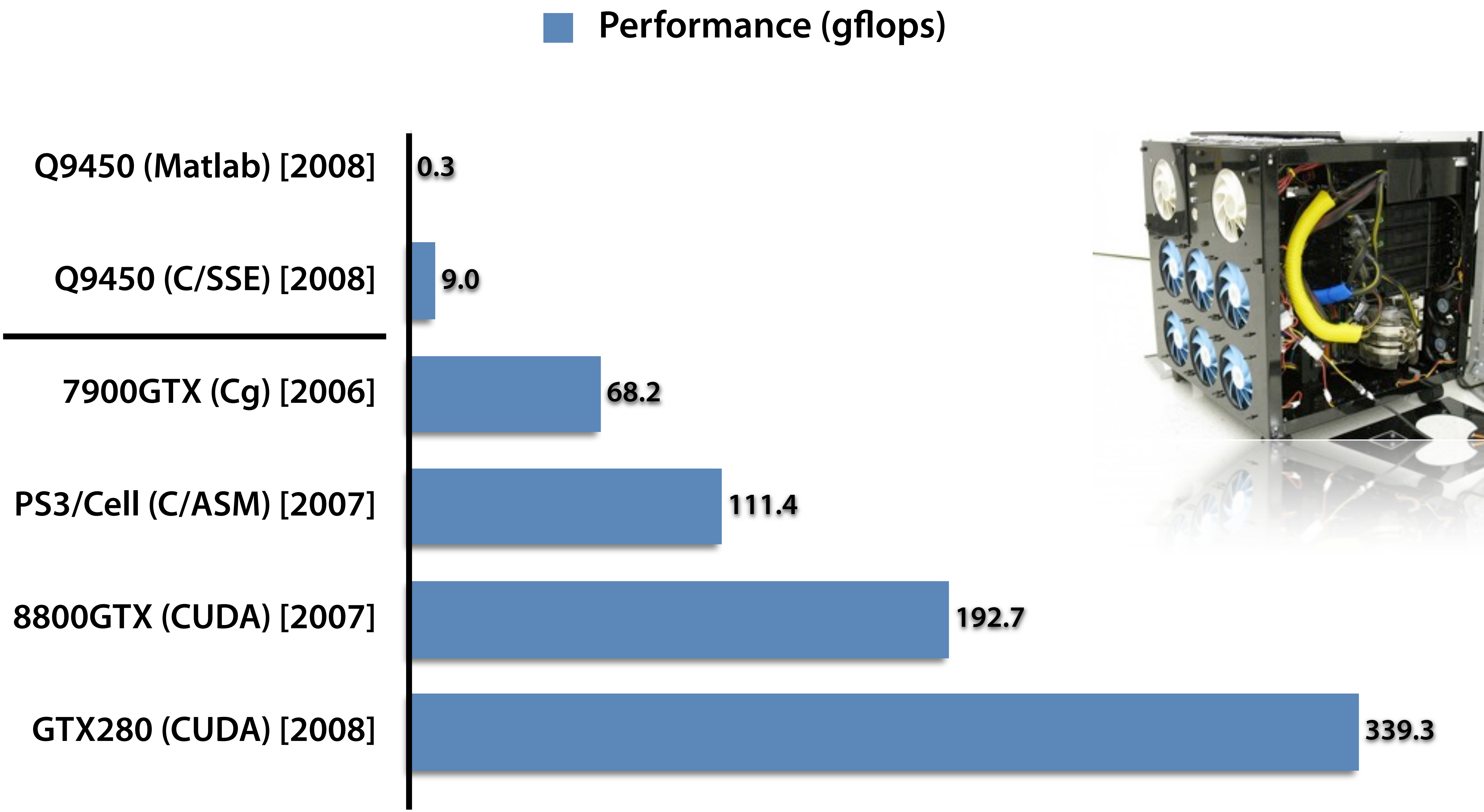

Need for speed
Hardware
Software
Science

What do we all want?

- Ease of use
- **Maximum raw speed**
- Ease of extension
- Hardware “agnostic”

A little story

You just finished your code...

A little story

You just finished your code...

1. You run it on one image: it works! 

A little story

You just finished your code...

1. You run it on one image: it works! 
2. You adjust your parameters: it's slow! 

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3. Your optimize your code: it’s fast now! 

A little story

You just finished your code...

1. You run it on one image: it works!

2. You adjust your parameters: it’s slow!

3. Your optimize your code: it’s fast now!

4. You run it on another image: it’s slow now!

A little story

You just finished your code...

1. You run it on one image: it works!

2. You adjust your parameters: it’s slow!

3. Your optimize your code: it’s fast now!

4. You run it on another image: it’s slow now!

5. You repeat or you stop...


Here are the keys
to Easy-High-Performance !

Meta-programming?

Meta-programming !

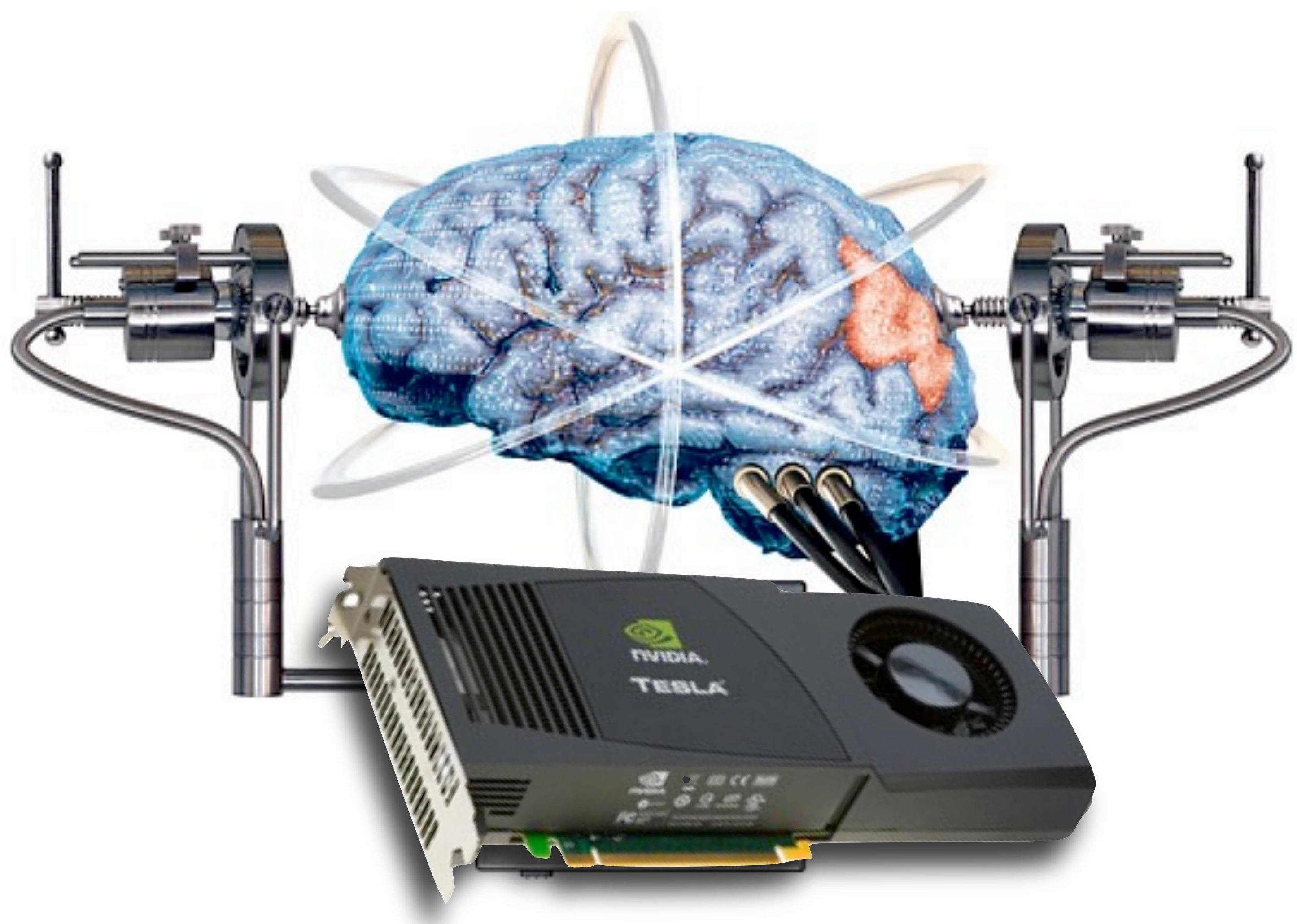
Leave the **grunt-programming** to the computer (i.e. auto-tuning like ATLAS or FFTW)

- Dynamically compile **specialized versions** of the same kernel for different conditions (~Just-in-Time Compilation (JIT))
- **Smooth** syntactic ugliness: unroll loops, index un-indexable registers
- **Dynamic**, empirical run-time **tuning**

Meta-programming!

"Instrumentalize" your solutions:

- Block size
- Work size
- Loop unrolling
- Pre-fetching
- Spilling
- **etc.**



Meta-programming!

Let the computer find the **optimal code**:

- brute–force search with a **global objective**
- machine–learning approach with **local objectives** and **hidden variables** (advanced)
  - eg. PyCuda makes this easy:
    - Access properties of compiled code: `func.{registers,lmem,smem}`
    - Exact GPU timing via events
    - Can calculate hardware-dependent MP occupancy

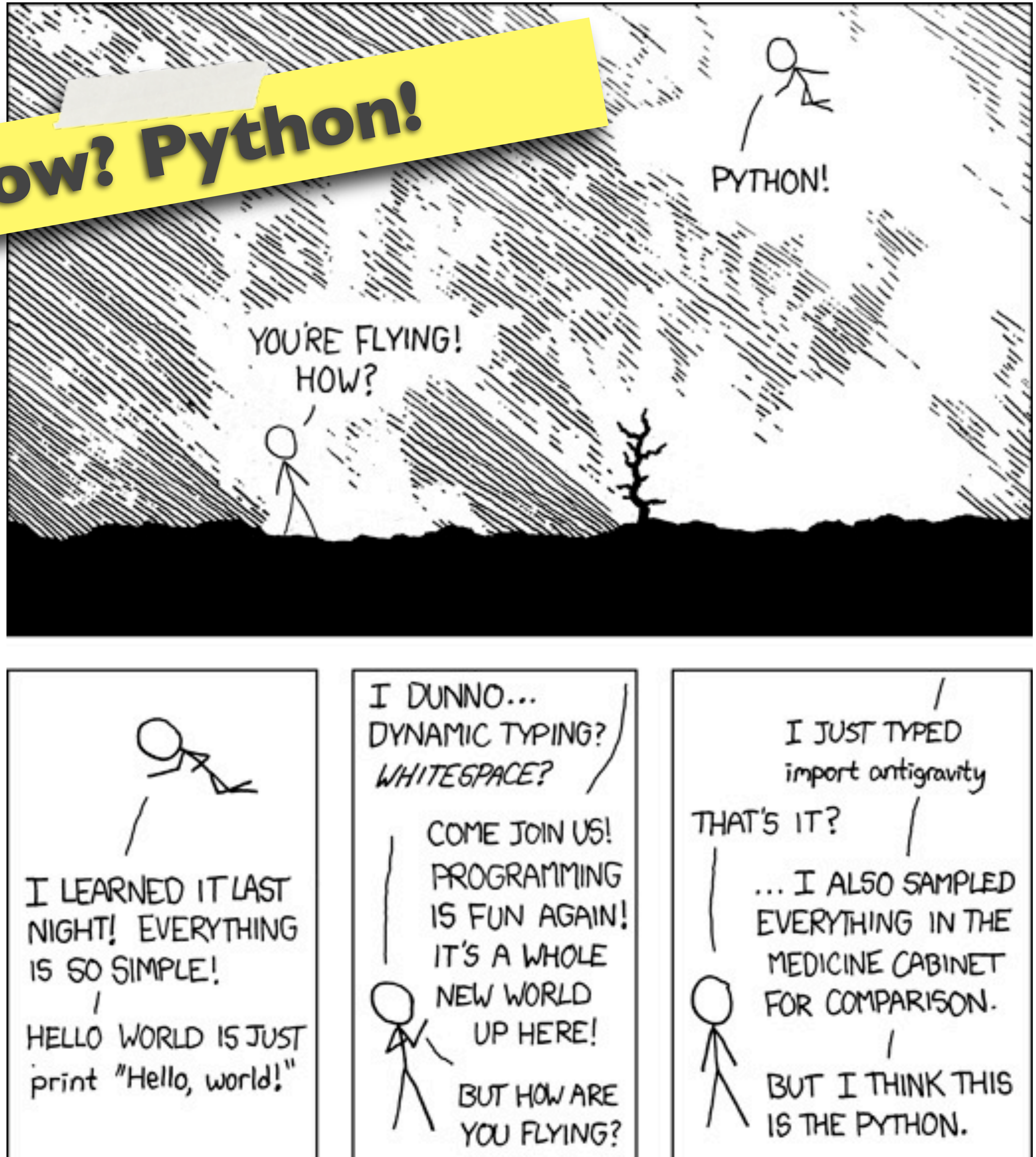
Meta-programming!

- GPU Metaprogramming using **PyCUDA**: Methods & Applications
  - Andreas Kloeckner (Brown)
  - Friday 1pm @ Empire

How ?

Our mantra: always use the right tool !

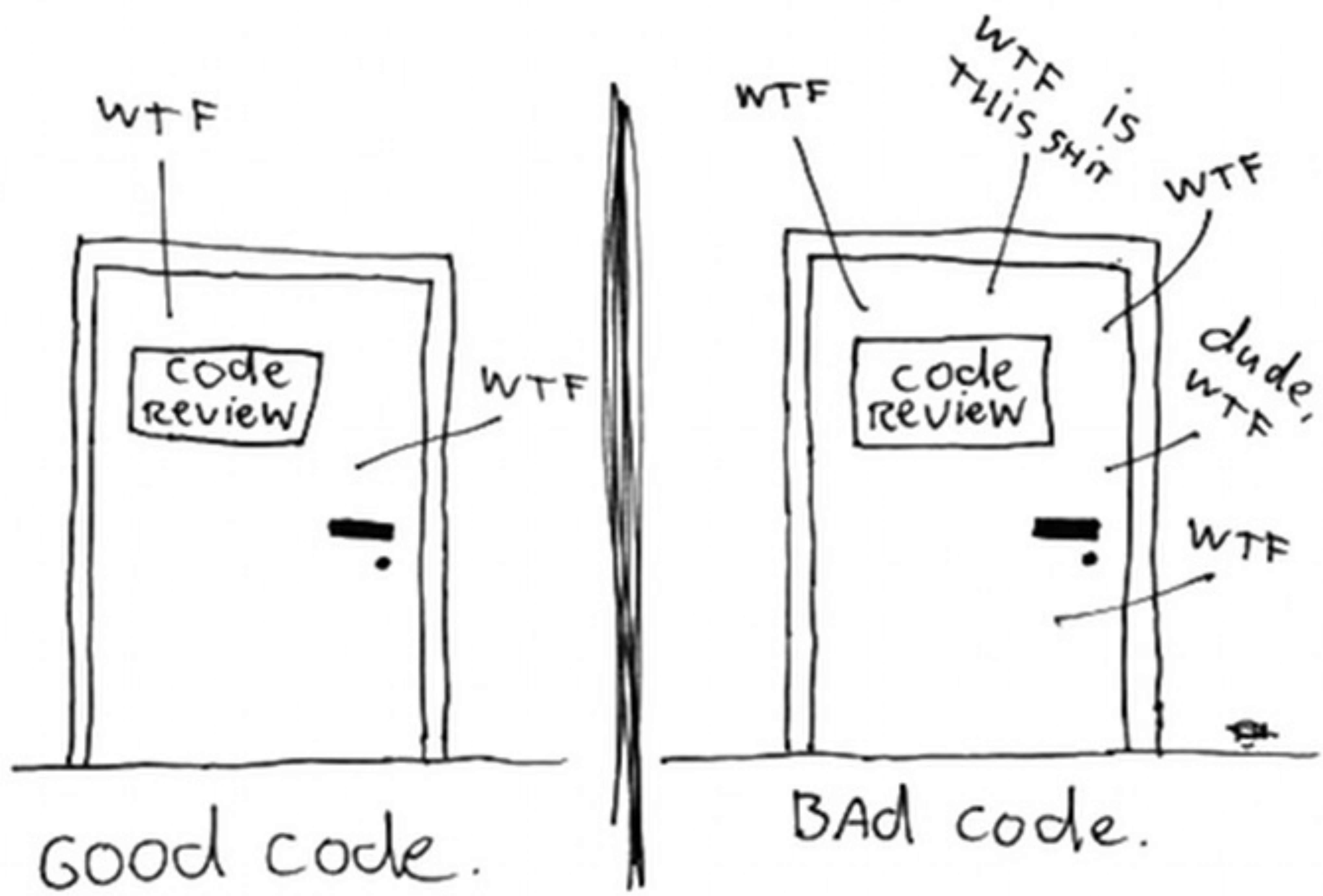
How? Python!



PYTHON!
YOU'RE FLYING! HOW?
I LEARNED IT LAST NIGHT! EVERYTHING IS SO SIMPLE!
HELLO WORLD IS JUST print "Hello, world!"
I DUNNO... DYNAMIC TYPING? WHITESPACE?
COME JOIN US! PROGRAMMING IS FUN AGAIN! IT'S A WHOLE NEW WORLD UP HERE!
BUT HOW ARE YOU FLYING?
I JUST TYPED import antigravity
THAT'S IT?
... I ALSO SAMPLED EVERYTHING IN THE MEDICINE CABINET FOR COMPARISON.
BUT I THINK THIS IS THE PYTHON.

Meta-programming requires **careful engineering**

Meta-programming requires **careful engineering**



Need for speed
Hardware
Software
Science

The Approach:
Forward Engineering the Brain

REVERSE

Study
Natural System

⇄

FORWARD

Build
Artificial System

The Approach:
Forward Engineering the Brain

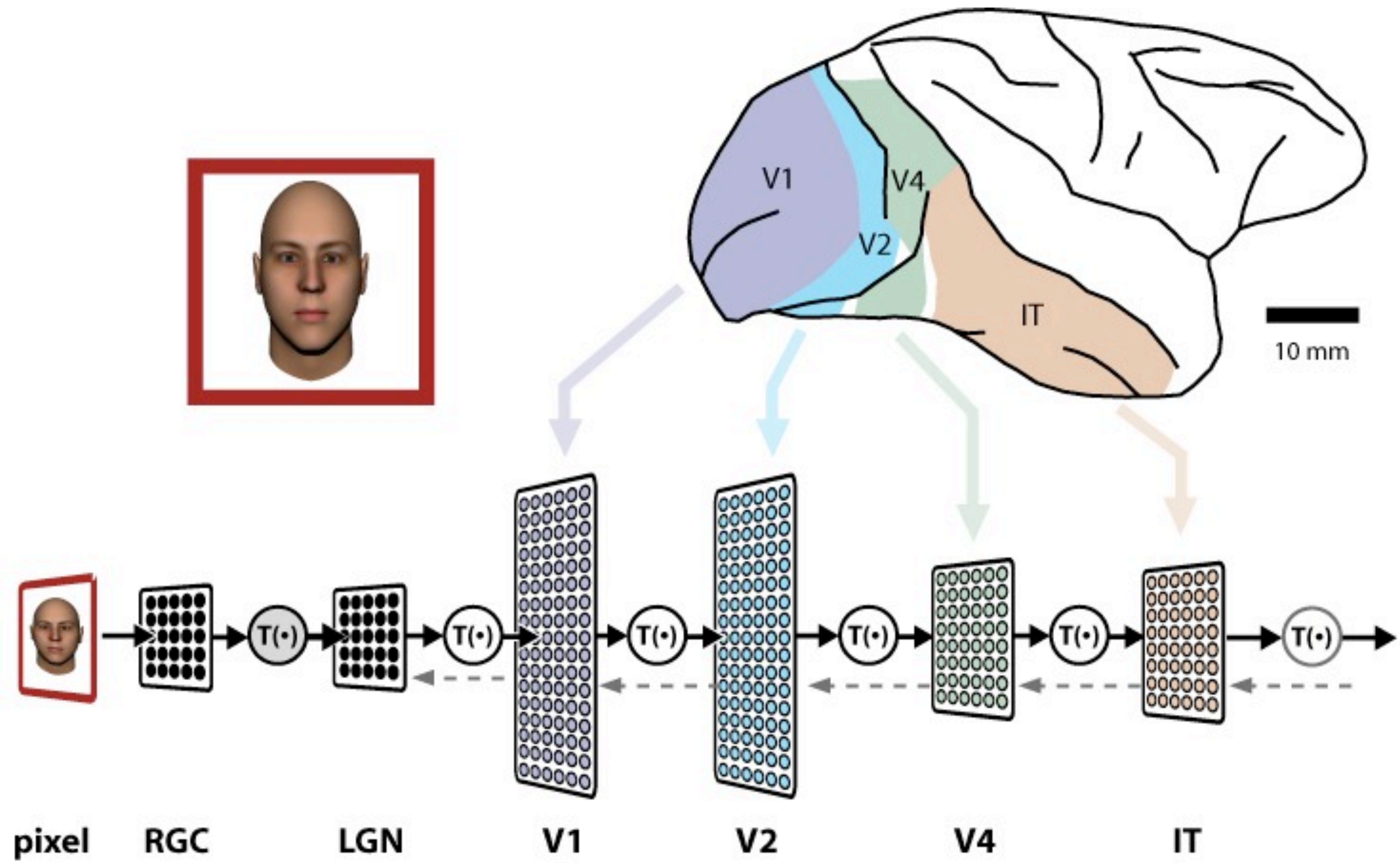
REVERSE

Study
Natural System

FORWARD

Build
Artificial System

Visual System



How are things done normally?

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Usual Formula:

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1) One grad student

How are things done normally?

Usual Formula:

1) **One grad student**

2) **One Model** (size limited by runtime)

How are things done normally?

Usual Formula:

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3) Performance numbers on a few standard test sets

How are things done normally?

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4) yay. we. rock.

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5) One Ph.D.

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Usual Formula:

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5) One Ph.D.

Doing things a little bit differently

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1) One grad student

Doing things a little bit differently

1) **One grad student**

2) **~~One~~ Hundreds of Thousands of BIG Models**

Doing things a little bit differently

1) One grad student

2) ~~One~~ Hundreds of Thousands of BIG Models

3) Performance numbers on a few standard test sets

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Doing things a little bit differently

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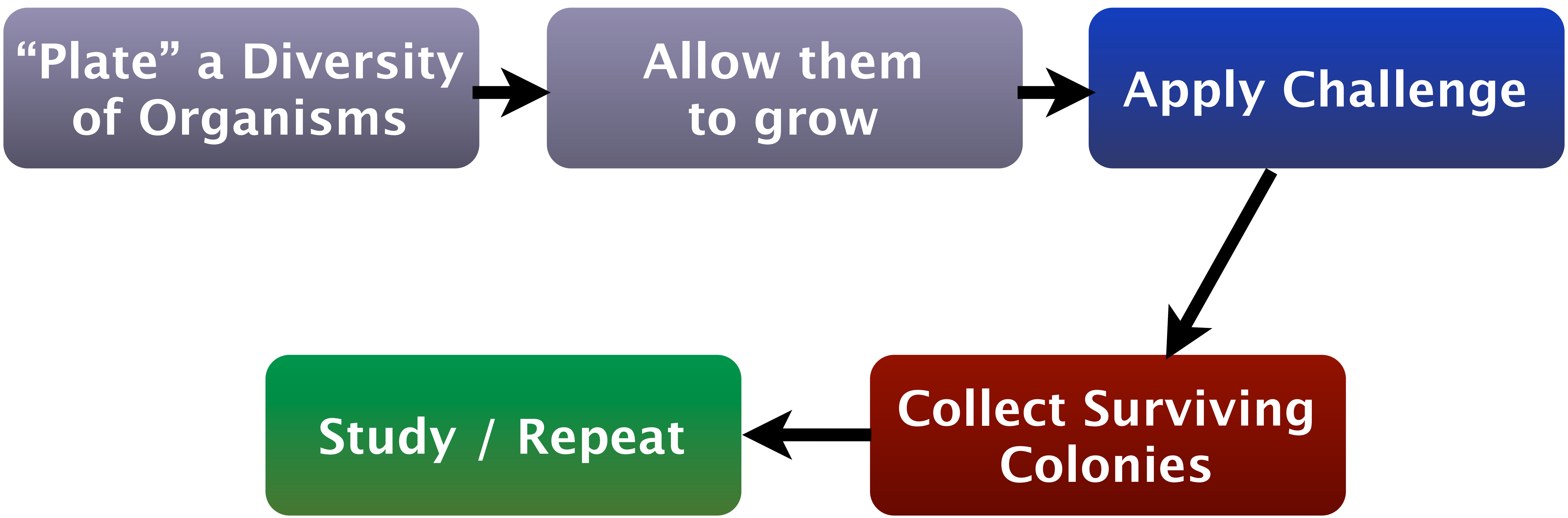
4) yay. we. rock.

5) ~~Hundreds of Thousands~~ One PhD ?

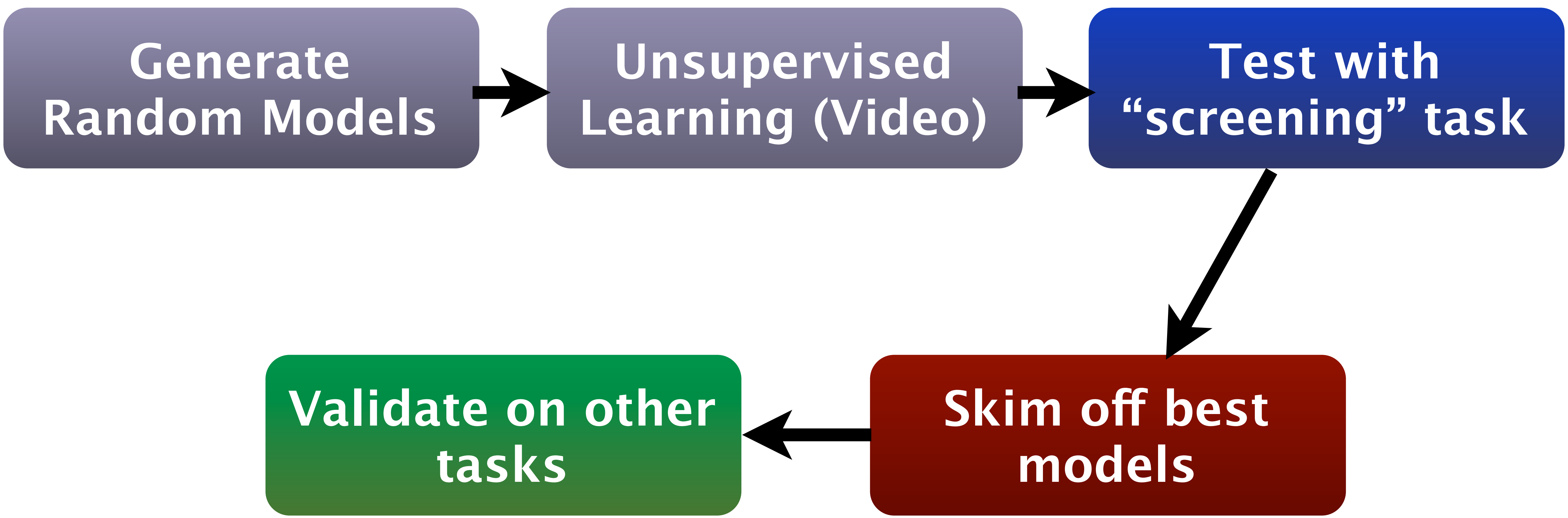
High-Throughput Screening

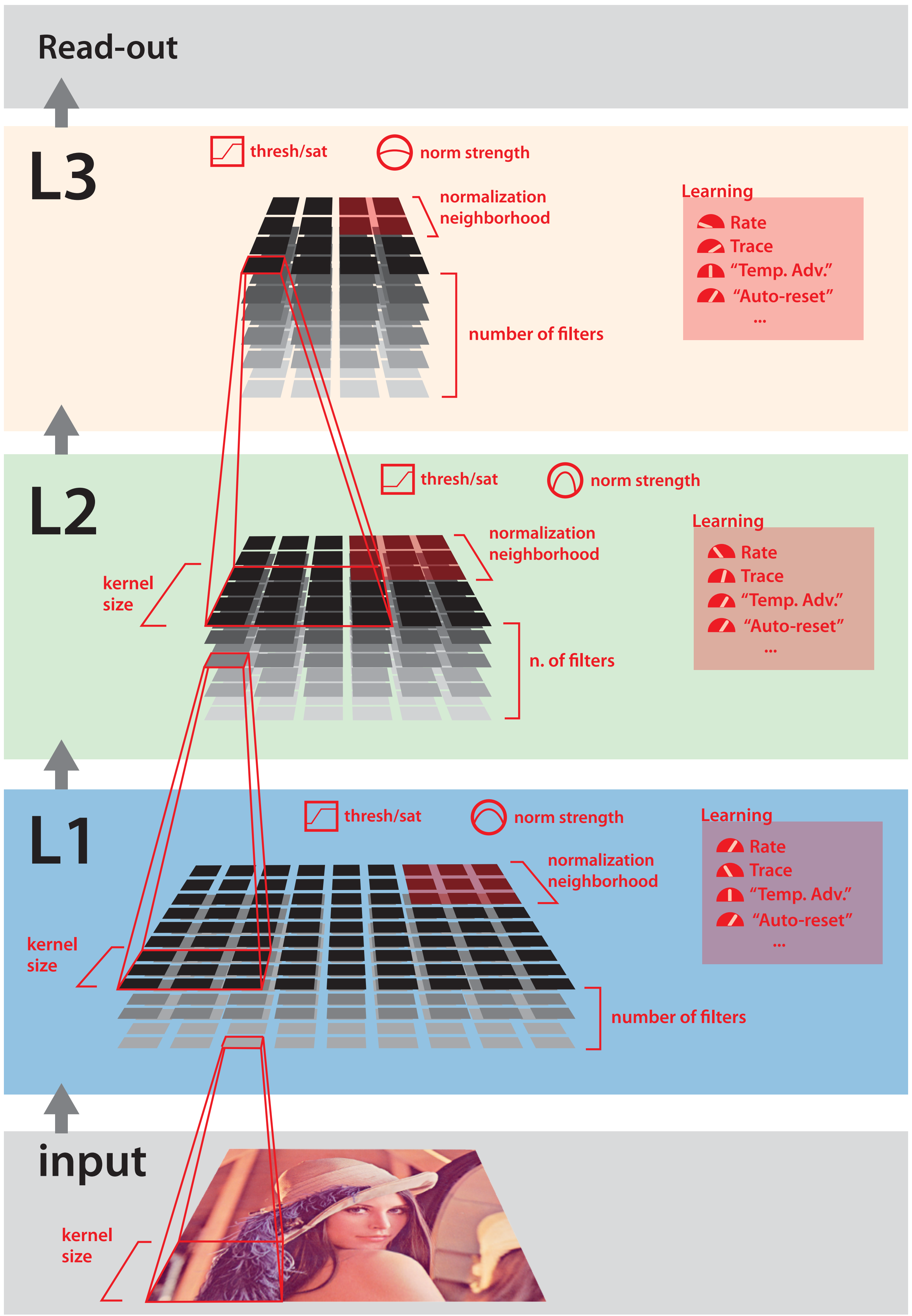
High-Throughput Screening

Pipeline: Biology



Pipeline: Biology-Inspired Vision





Read-out
L3
thresh/sat
norm strength
normalization neighborhood
number of filters
Learning
Rate
Trace
"Temp. Adv."
"Auto-reset"
...
L2
thresh/sat
norm strength
normalization neighborhood
kernel size
n. of filters
Learning
Rate
Trace
"Temp. Adv."
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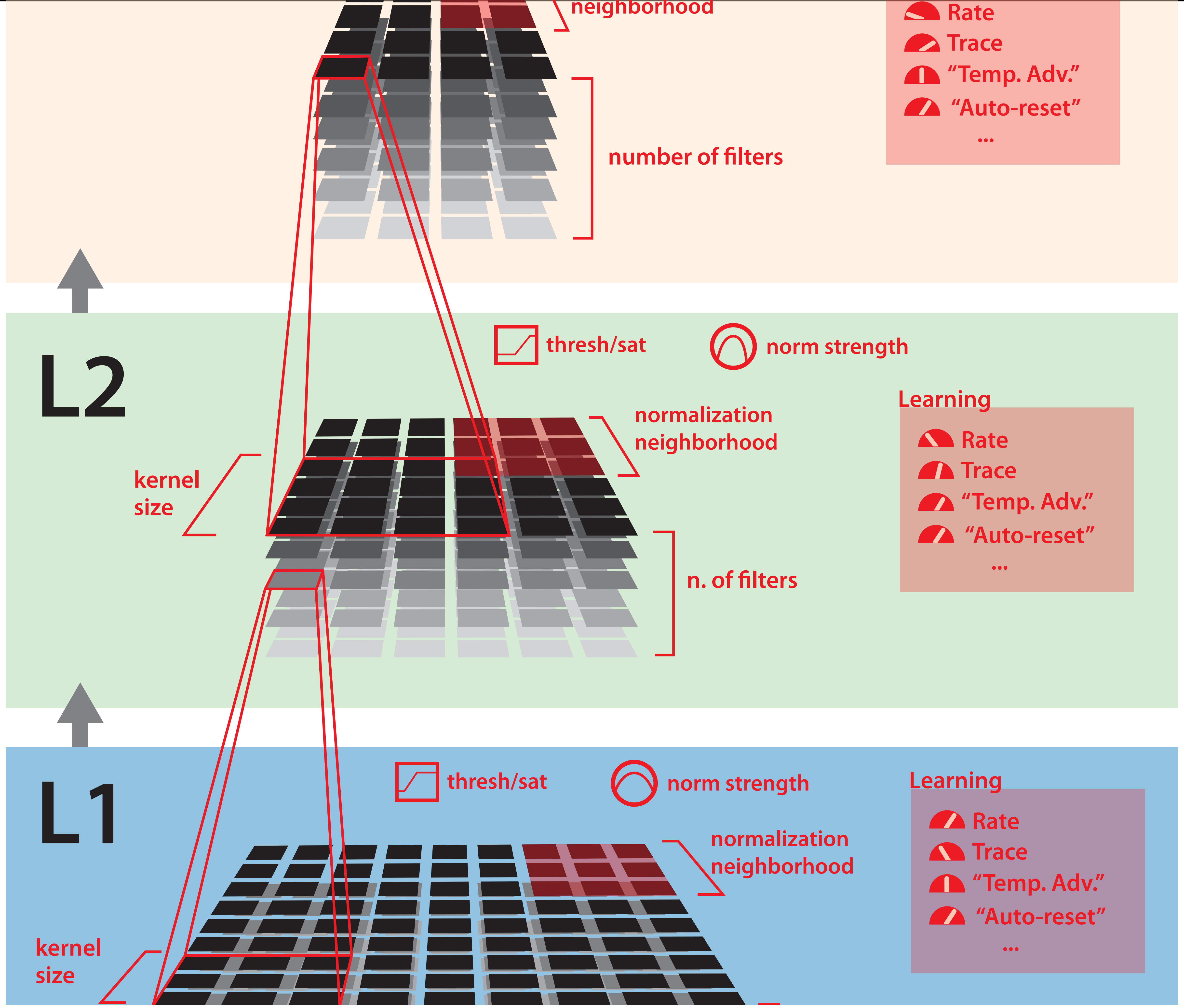
...
L1
thresh/sat
norm strength
normalization neighborhood
kernel size
number of filters
Learning
Rate
Trace
"Temp. Adv."
"Auto-reset"
...
input
kernel size



neighborhood
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number of filters
L2
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...
normalization neighborhood
kernel size
n. of filters
L1
thresh/sat
norm strength
Learning
Rate
Trace
"Temp. Adv."
"Auto-reset"
...
normalization neighborhood
kernel size

A Broad **Parametric** Model

Normalize

$N_i = Input_i / norm(Input_{neighborhd})$

Compute Filter Responses

$R_i = F_i \otimes N$

$R_i < thresh: R_i = thresh$

$R_i > sat: R_i = sat$

Determine a "Winning Filter"

$R_i' = (\sum T_k * H_k) * R_i$

winner: $max(R_i')$

Update Filter

$F_{winning} = F_{winning} + \text{learning rate} * N$

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(filters span the range of observed inputs)

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(filters span the range of observed inputs)

- **Privilege movement of filters in certain directions using temporal information**

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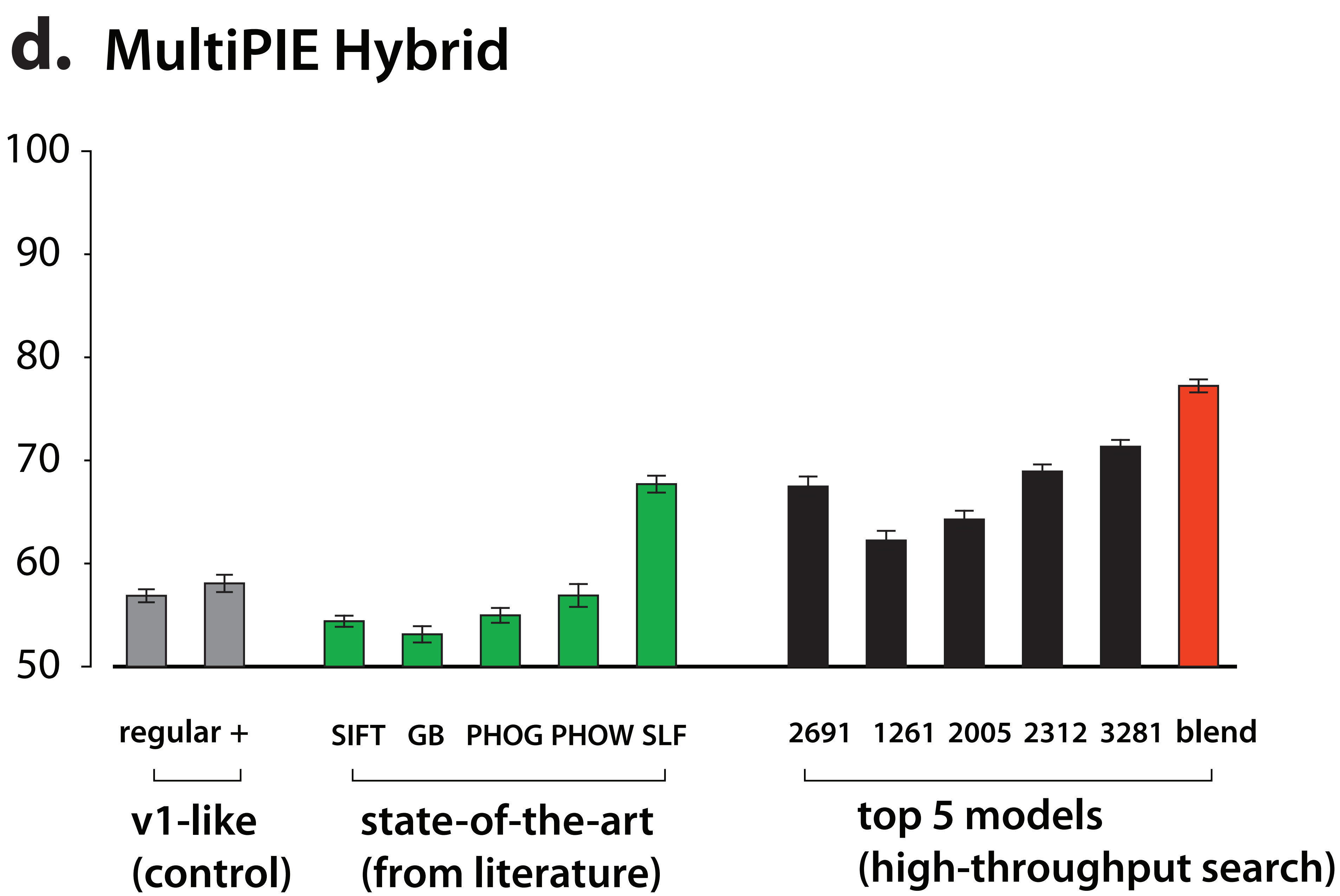
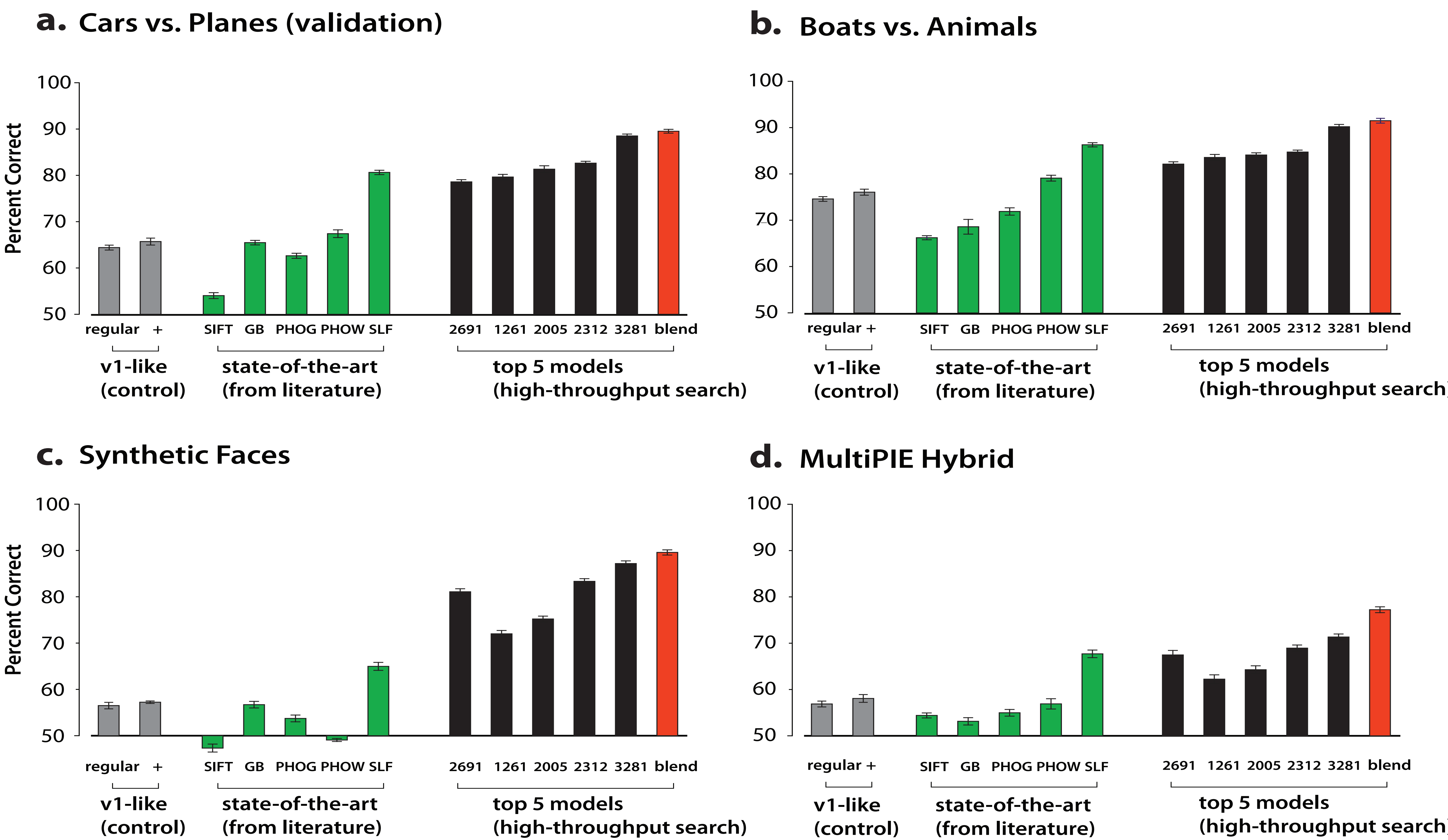
- **Optimize "Coverage"**
  (filters span the range of observed inputs)
- **Privilege movement of filters in certain directions using temporal information**
- **Expand dimensionality greatly and then scale back as layers progress**

State-of-the-art performance



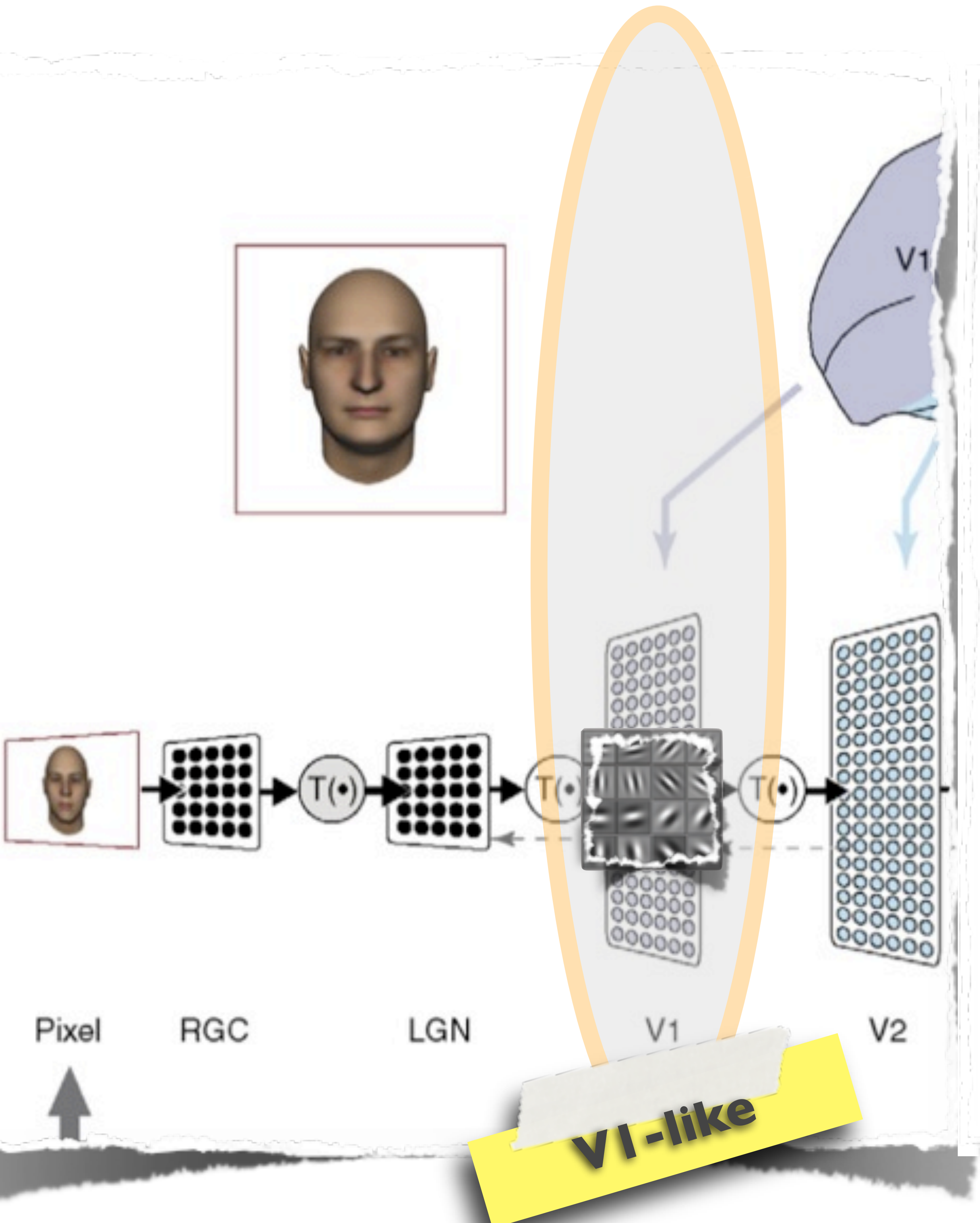
Pinto, DiCarlo, Cox (in review)

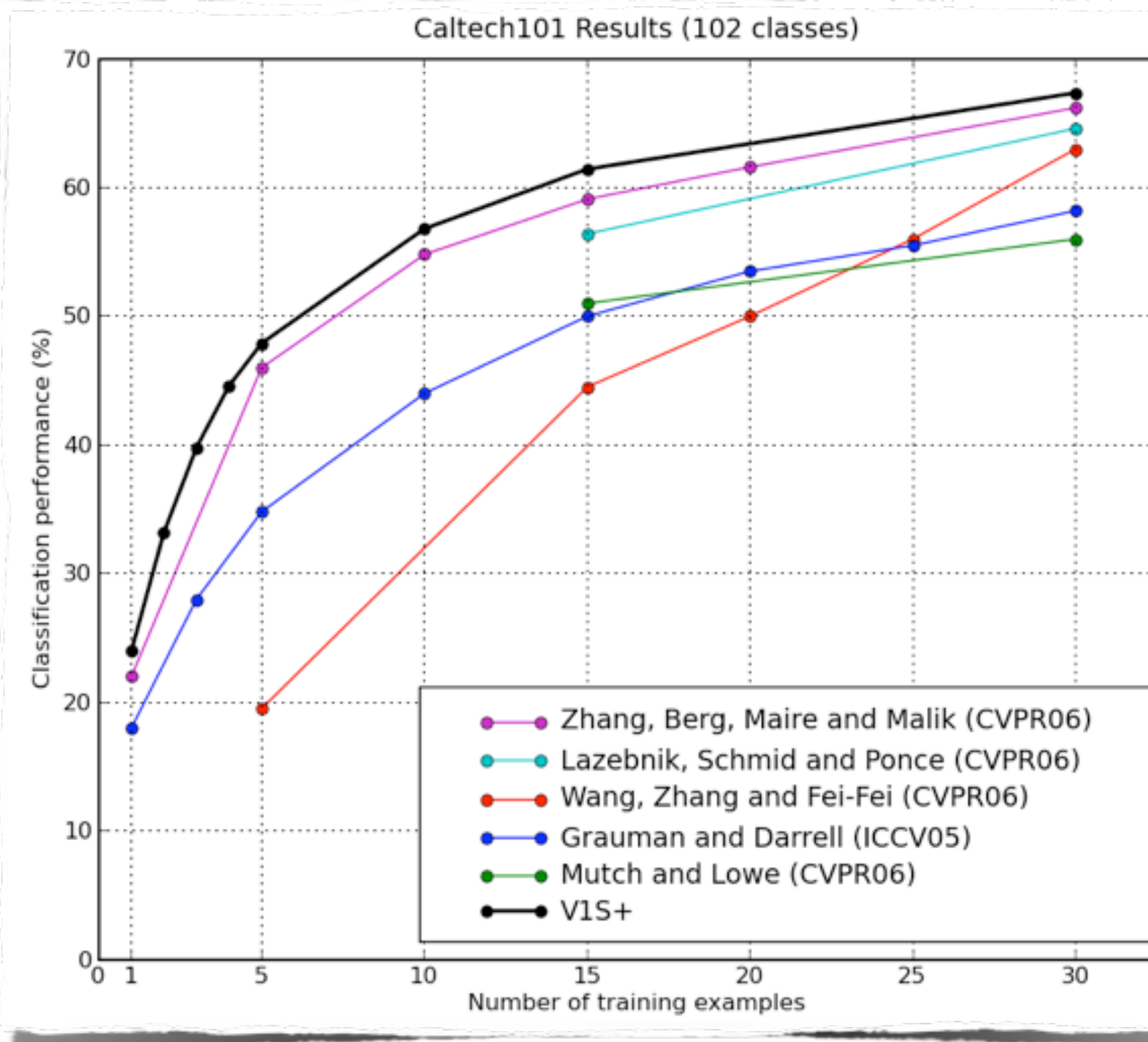
State-of-the-art performance



Pinto, DiCarlo, Cox (in review)

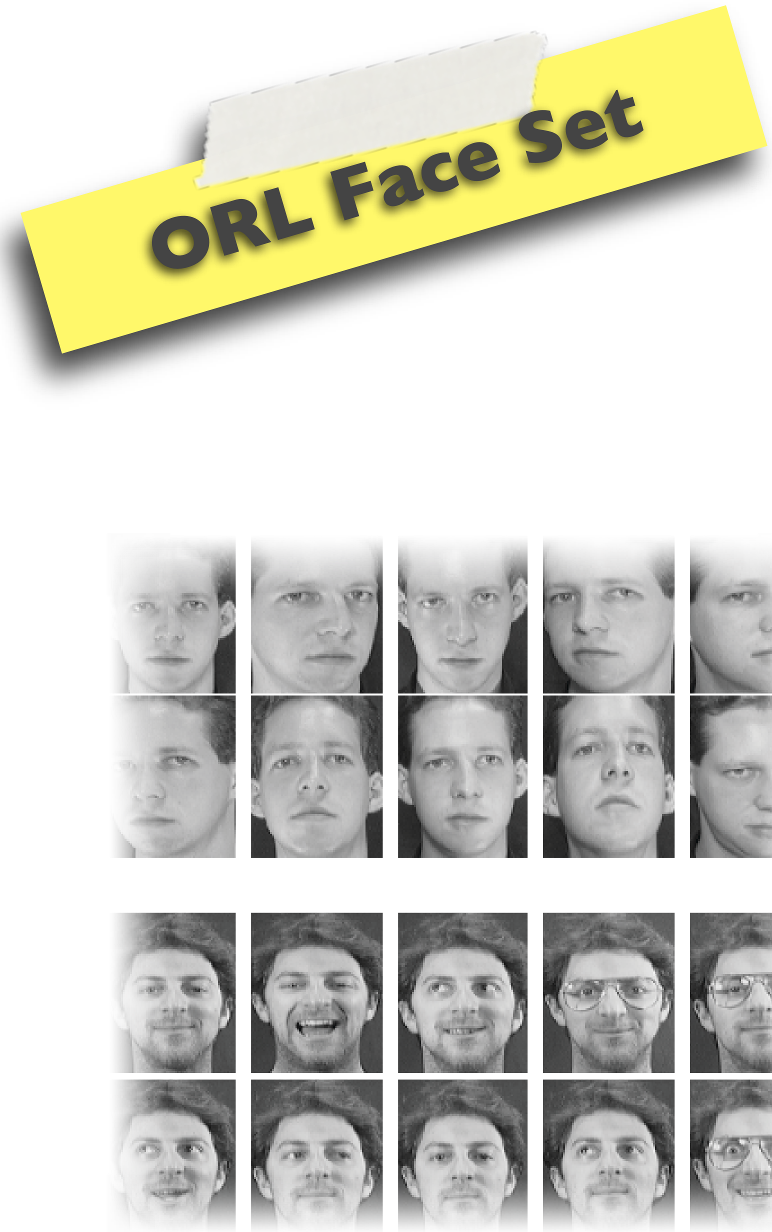
State-of-the-art performance

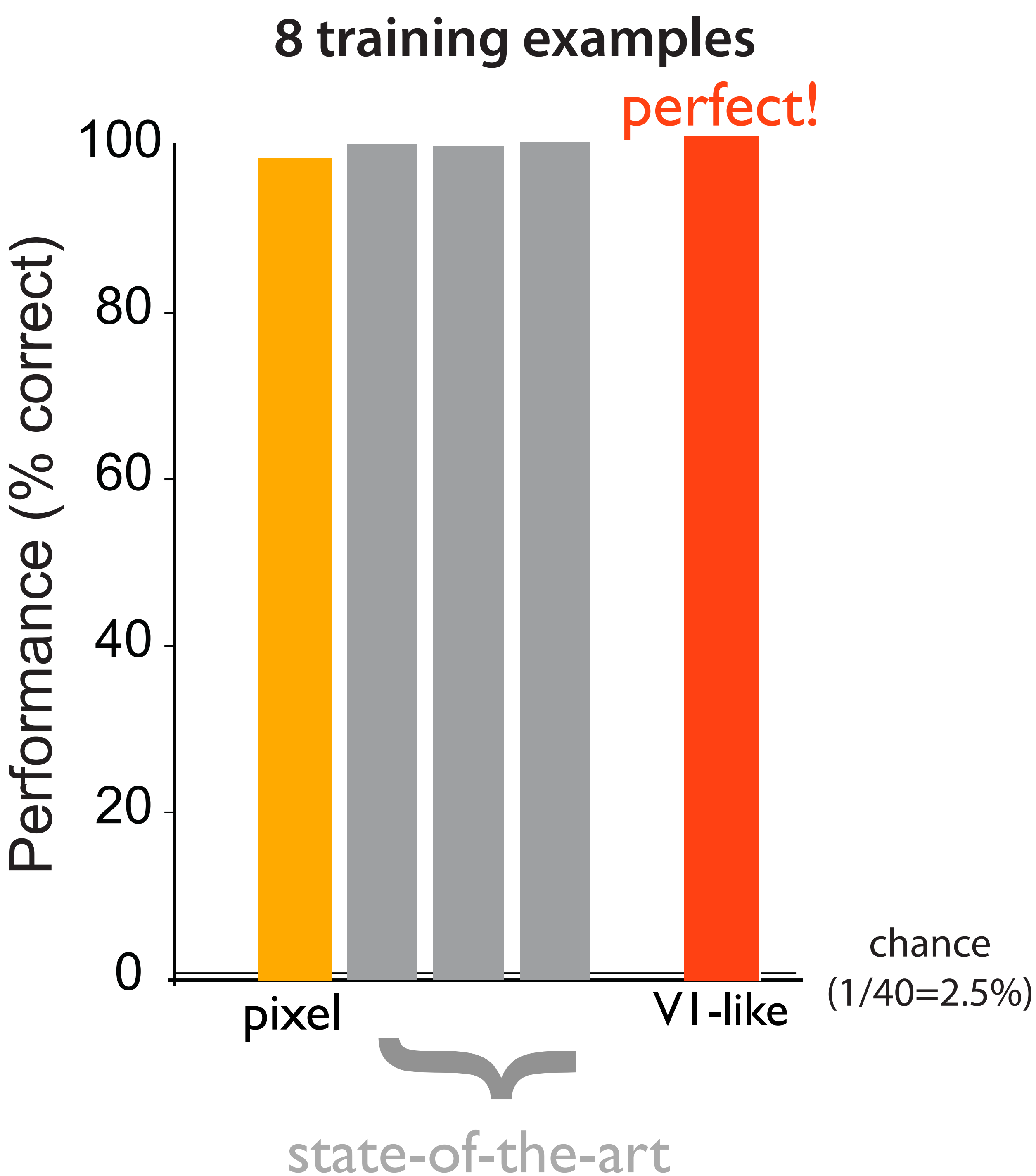




Pinto, Cox, DiCarlo PLoS08

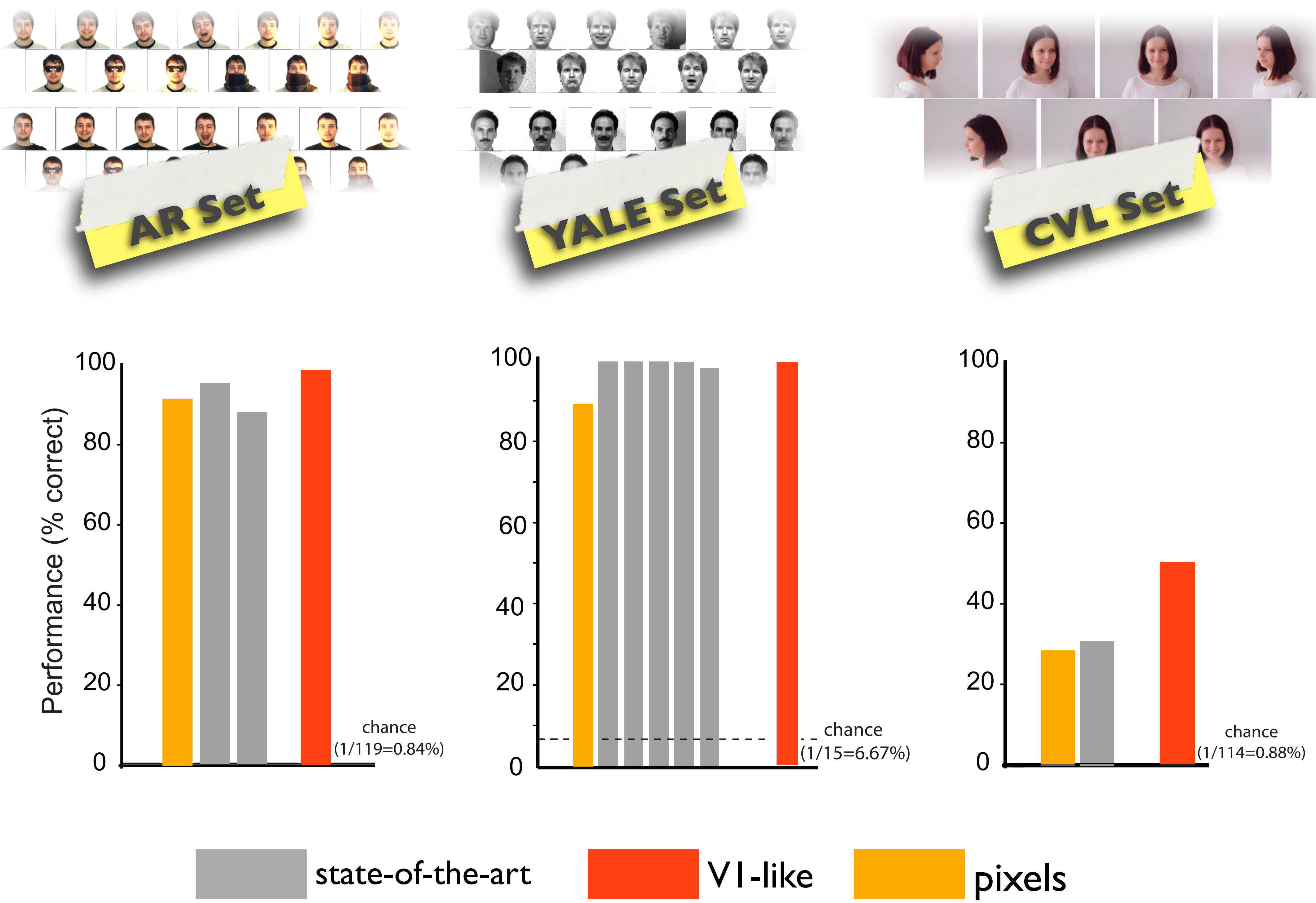
State-of-the-art performance





Pinto, DiCarlo, Cox ECCV08

State-of-the-art performance



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State-of-the-art performance

LFW Face Set

Reference	Methods	Performance
Huang08 [6]	Nowak [8]	73.93%±0.49
	MERL	70.52%±0.60
	Nowak+MERL	76.18%±0.58
Wolf08 [17]	descriptor-based	70.62%±0.57
	one-shot-learning*	76.53%±0.54
	hybrid*	78.47%±0.51
This paper	Pixels/MKL	68.22%±0.41
	V1-like/MKL	**79.35%±0.55**

Table 3. Average performance comparison with the current state-of-the-art on LFW. *note that the "one-shot-learning" and "hybrid" methods from [17] can't directly be compared to ours as they exploit the fact that individuals in the training and testing sets are mutually exclusive (i.e. using this property, you can build a powerful one-shot-learning classifier knowing that each test example is *different* from all the training examples, see [17] for more details. Our decision not to use such techniques effectively handicaps our results relative to reports that use them).

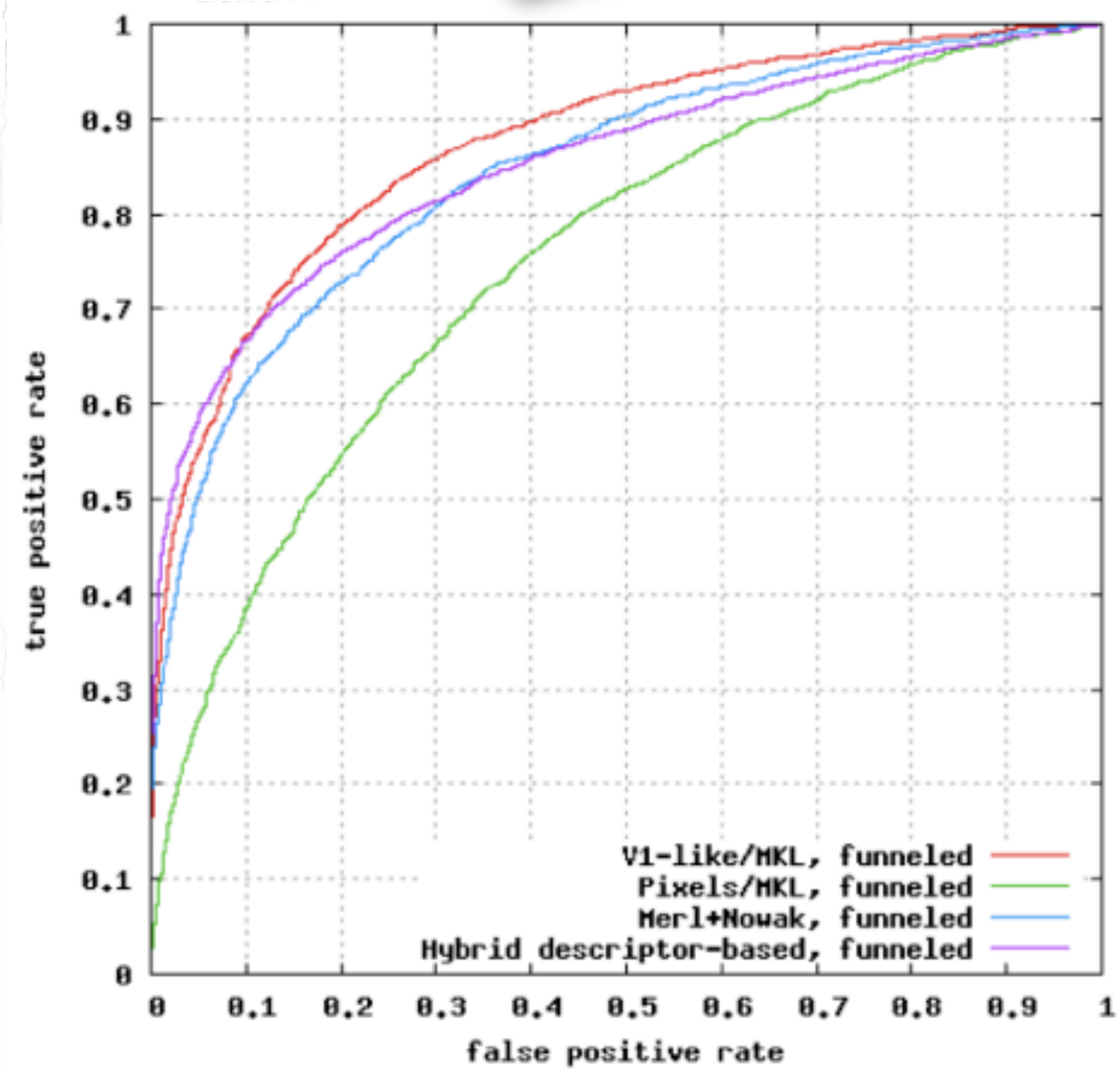

Figure 1. ROC curve comparison with the current state-of-the ar
on LFW. These curves were generated using the standard proce
dure described in [24].

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