Scheduling Array Operations

Juuso Haavisto (University of Oxford), October 2022

Static Semantics

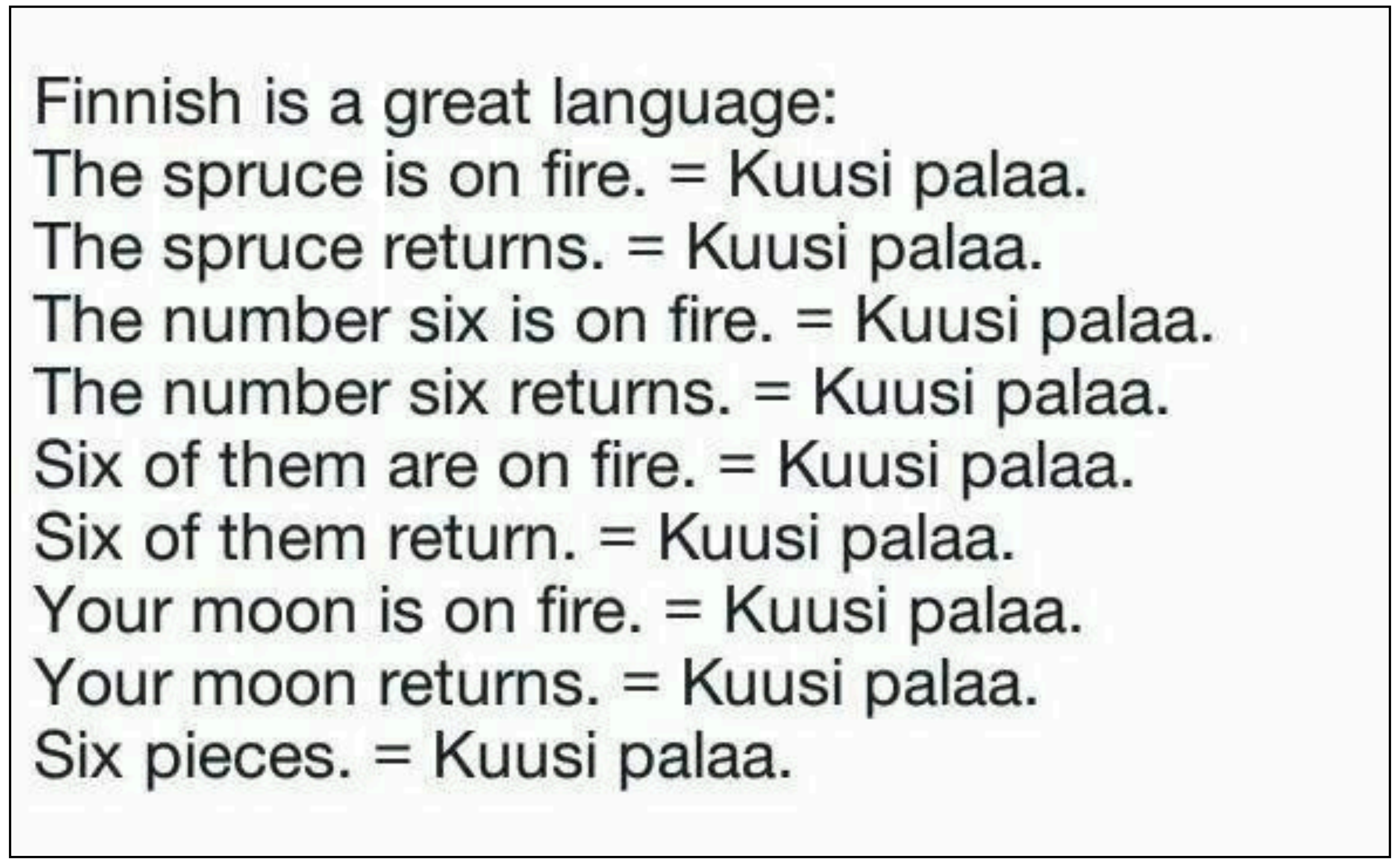
Ability to detect correctness errors before execution

Statically absurd situation:
Waterfal (Escher, 1961)

Rank Polymorphism

Language property where semantically same thing means multiple things depending on the context

Challenge: building connection between static semantics



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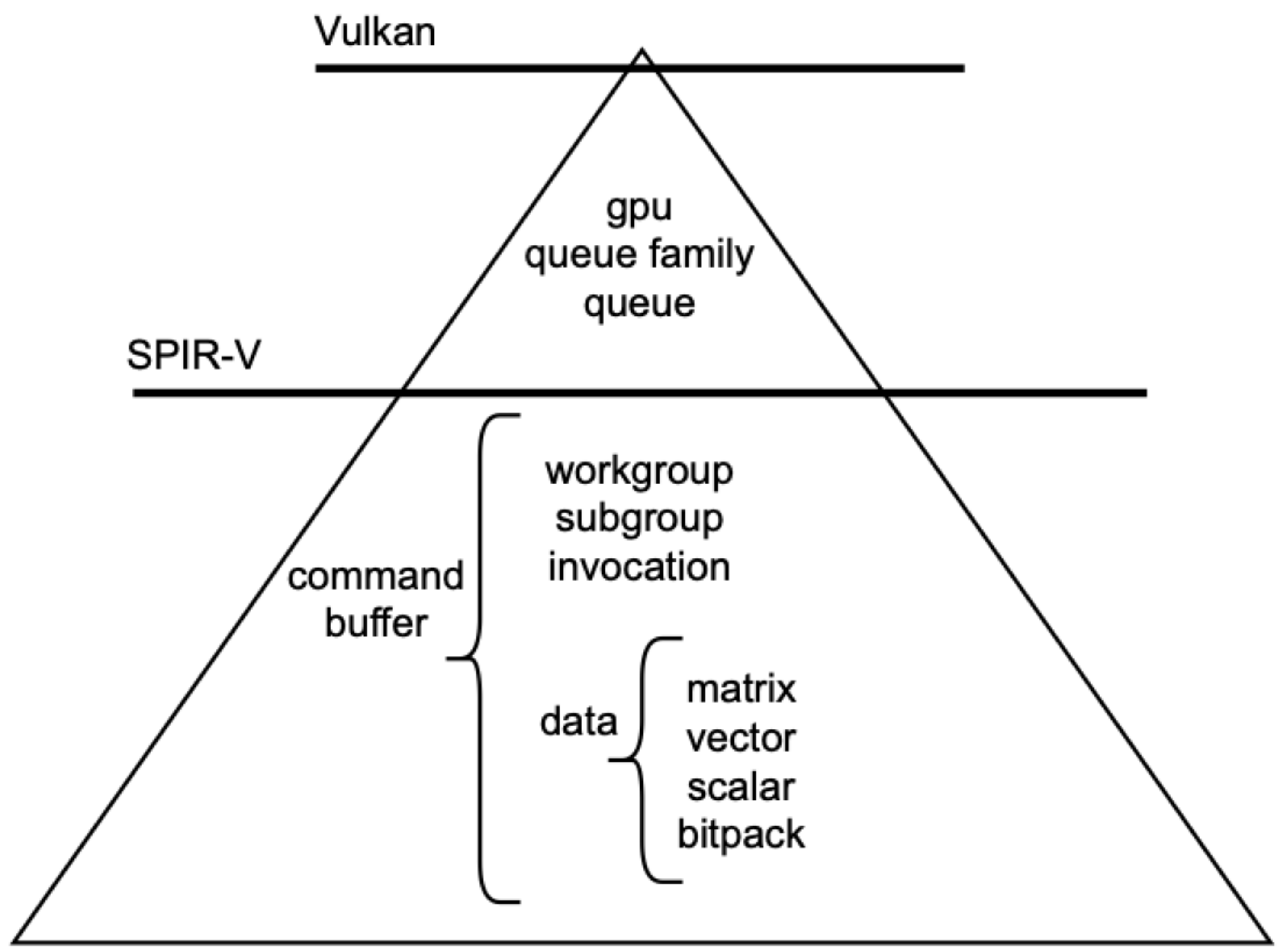
A certain kind of rank polymorphism in action

Scheduling

With static rank polymorphism, we can give GPU a data structure that it understands, and from which to derive scheduling schemes for multi-core use

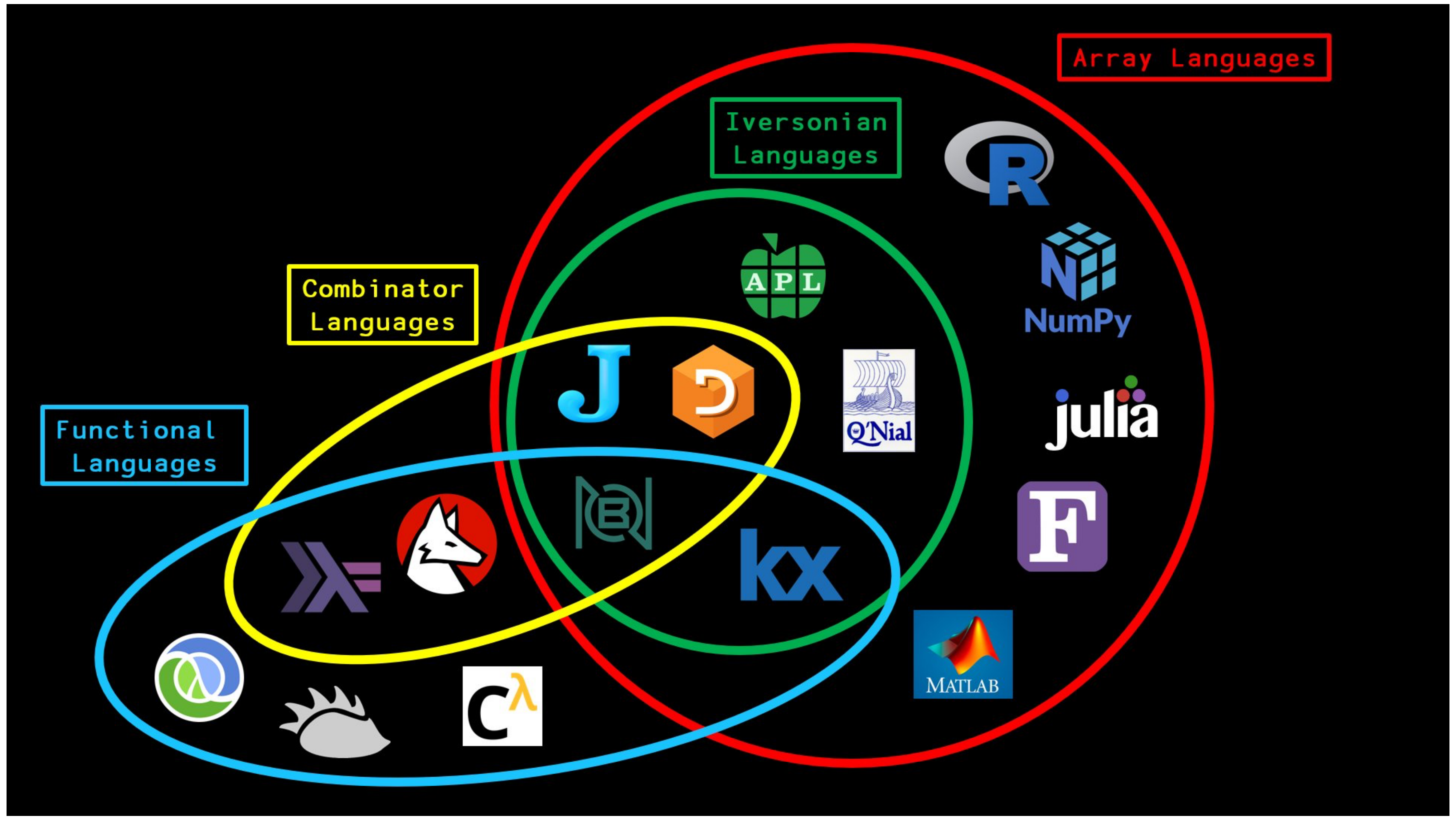


Hierarchy of GPU

Big picture

“Moving Haskell towards Dyalog APL”

- APL programmers “see” a lot about their programs
- but the computer… not so much
- my research is about revisiting what the computer can “see” without adding new language semantics



“Array Languages vs Iversonian Languages vs Combinator Languages vs Functional Languages” - Conor Hoekstra @code_report

Max Pooling example, Rodrigo Serrão

MX←{⌈⌿[2],[2 3]{ω}⌺(2 2ρ2)⊃Z[α]←⊂ω}

```
      M
 1  2  3  4
 5  6  7  8
 9 10 11 12
13 14 15 16
      {⊂⍵}⌺(2 2)⊢M
┌─────┬─────┬─────┐
│1 2  │2 3  │3 4  │
│5 6  │6 7  │7 8  │
├─────┼─────┼─────┤
│5  6 │ 6  7│ 7  8│
│9 10 │10 11│11 12│
├─────┼─────┼─────┤
│ 9 10│10 11│11 12│
│13 14│14 15│15 16│
└─────┴─────┴─────┘
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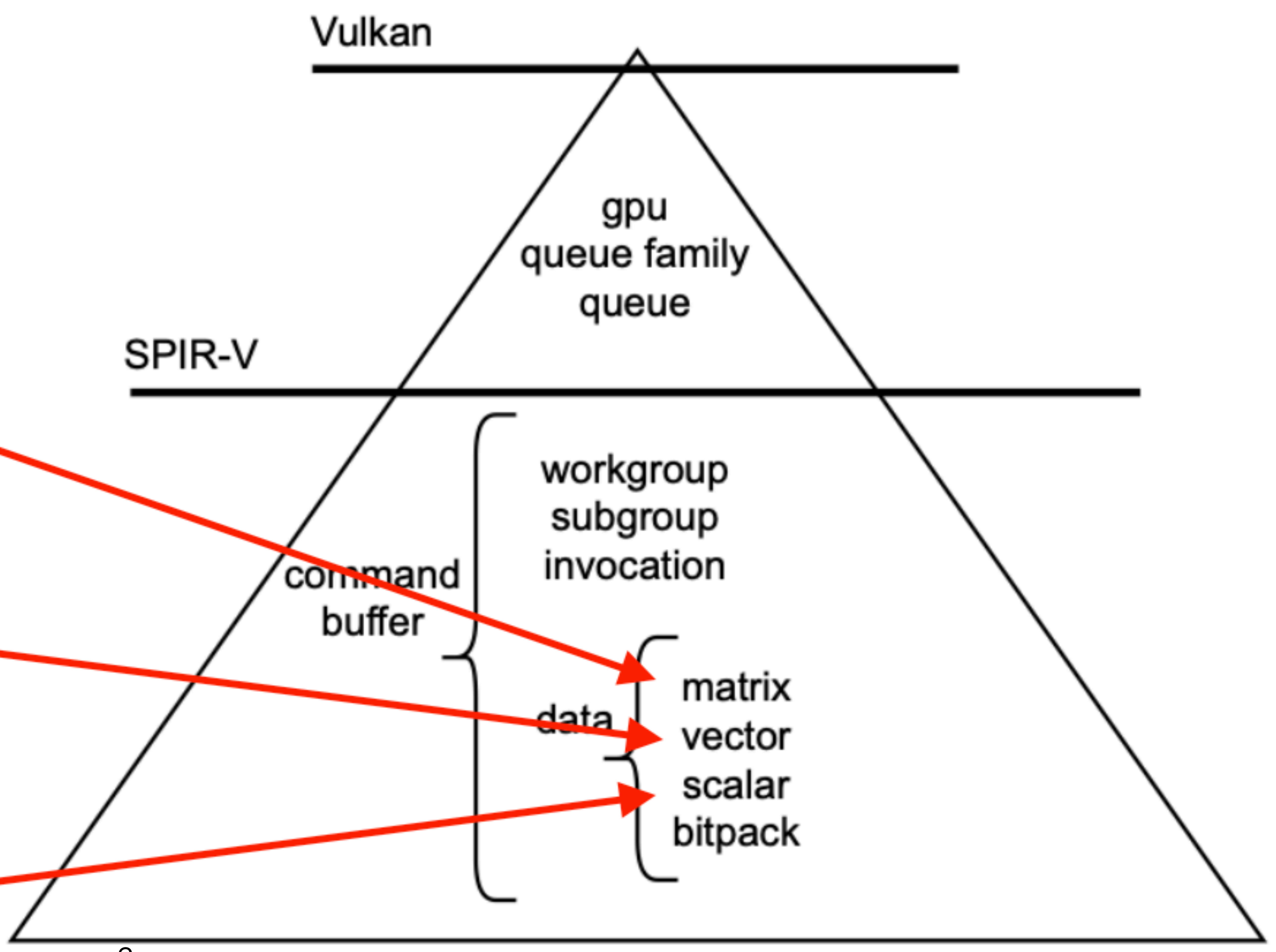
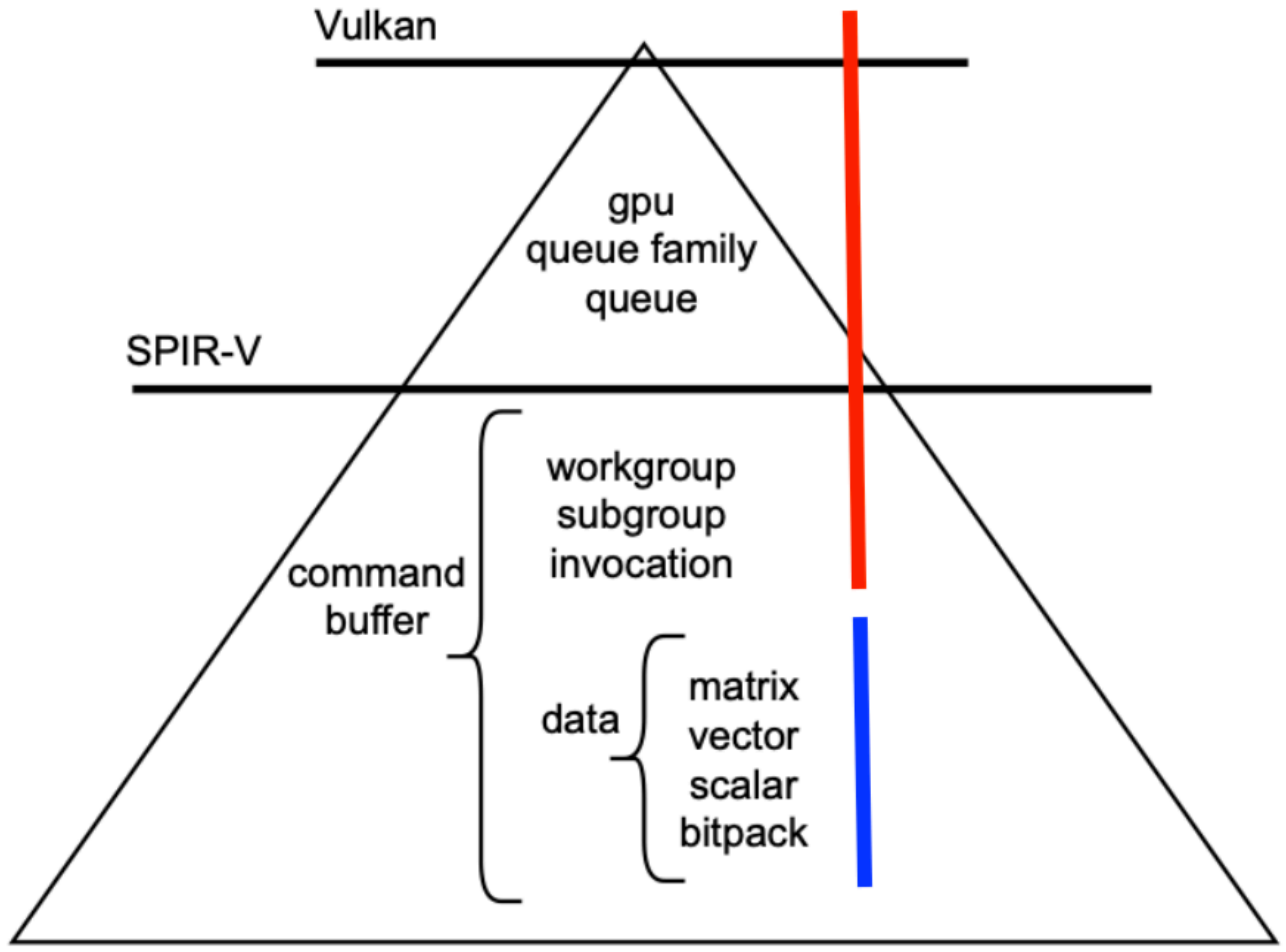


Modern Hardware

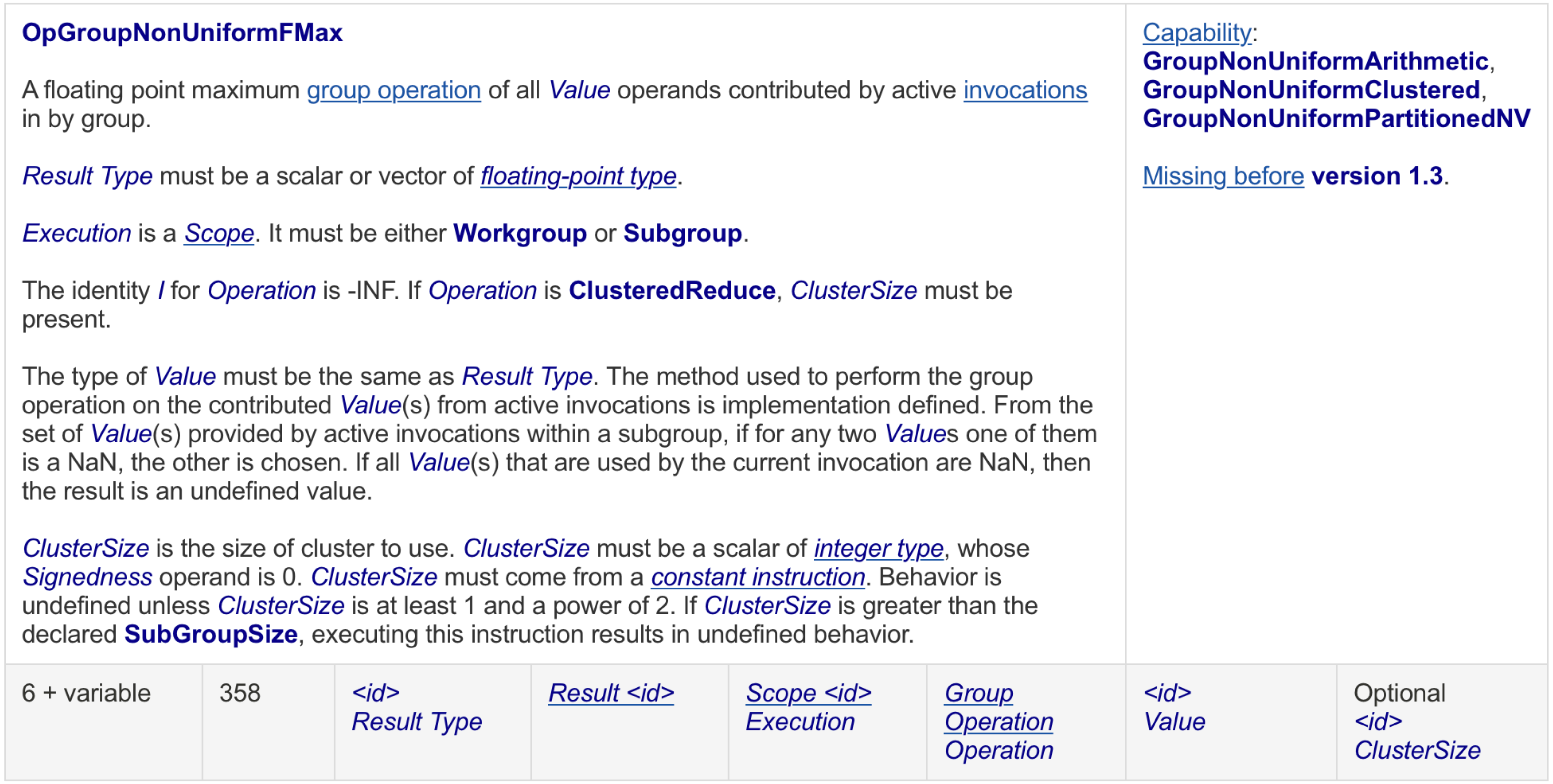
Separation in “what” and “how” we compute things

- how we compute — the red part
  -> build on top of data

- what we compute — the blue part
  -> APL programmers excel here



- weirdly enough GPU people have created instructions for APL operations already
- … but using the correct instruction with correct parameters requires compilation



OpGroupNonUniformFMax

A floating point maximum group operation of all *Value* operands contributed by active invocations in by group.

Result Type must be a scalar or vector of *floating-point type*.

Execution is a *Scope*. It must be either **Workgroup** or **Subgroup**.

The identity *I* for *Operation* is -INF. If *Operation* is **ClusteredReduce**, *ClusterSize* must be present.

The type of *Value* must be the same as *Result Type*. The method used to perform the group operation on the contributed *Value*(s) from active invocations is implementation defined. From the set of *Value*(s) provided by active invocations within a subgroup, if for any two *Value*s one of them is a NaN, the other is chosen. If all *Value*(s) that are used by the current invocation are NaN, then the result is an undefined value.

ClusterSize is the size of cluster to use. *ClusterSize* must be a scalar of *integer type*, whose *Signedness* operand is 0. *ClusterSize* must come from a *constant instruction*. Behavior is undefined unless *ClusterSize* is at least 1 and a power of 2. If *ClusterSize* is greater than the declared **SubGroupSize**, executing this instruction results in undefined behavior.

Capability:
GroupNonUniformArithmetic, **GroupNonUniformClustered**, **GroupNonUniformPartitionedNV**

Missing before **version 1.3**.

6 + variable	358	*<id>* *Result Type*	*Result <id>*	*Scope <id>* *Execution*	*Group Operation* *Operation*	*<id>* *Value*	Optional *<id>* *ClusterSize*

About me

My APL short-story

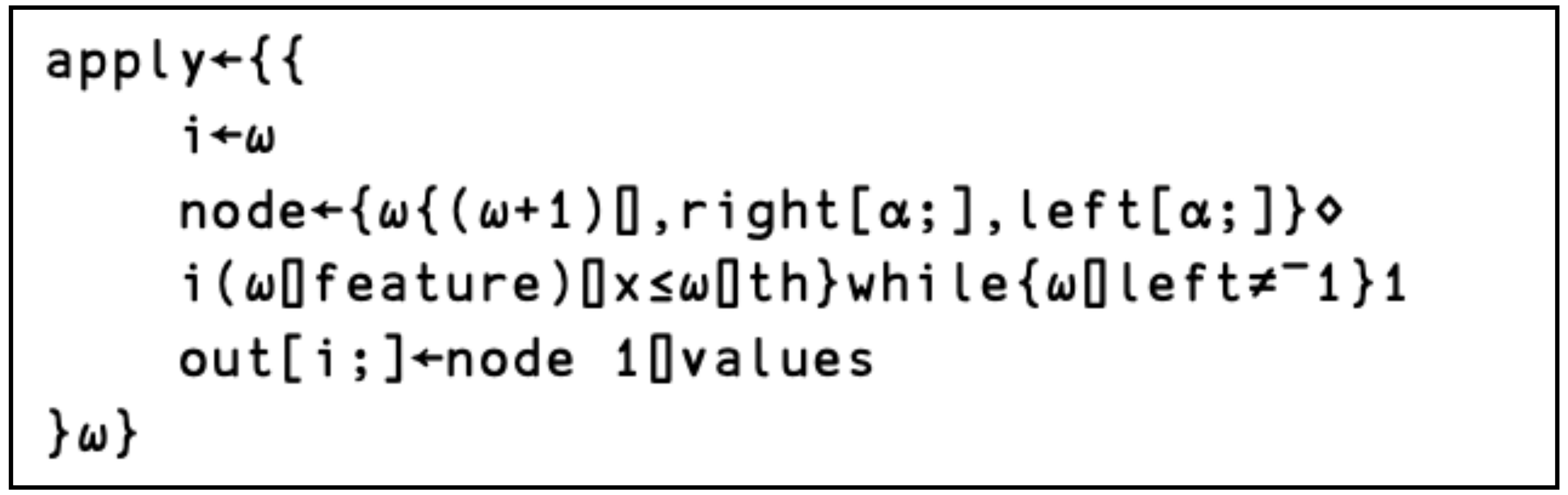
- learned about APL in 2018
- actually looked into it in 2019
- => love on first IDE (Dyalog)
- highly influenced by Aaron Hsu's YouTube talks and thesis

ELEMENTARY ALGEBRA

IBM PHILADELPHIA SCIENTIFIC CENTER
Data Processing Division
TECH. REPORT NO. 320-3001 JUNE 1971

K. E. IVERSON

Seemingly, I first learned about APL from this PDF book: Elementary Algebra, K.E. Iverson

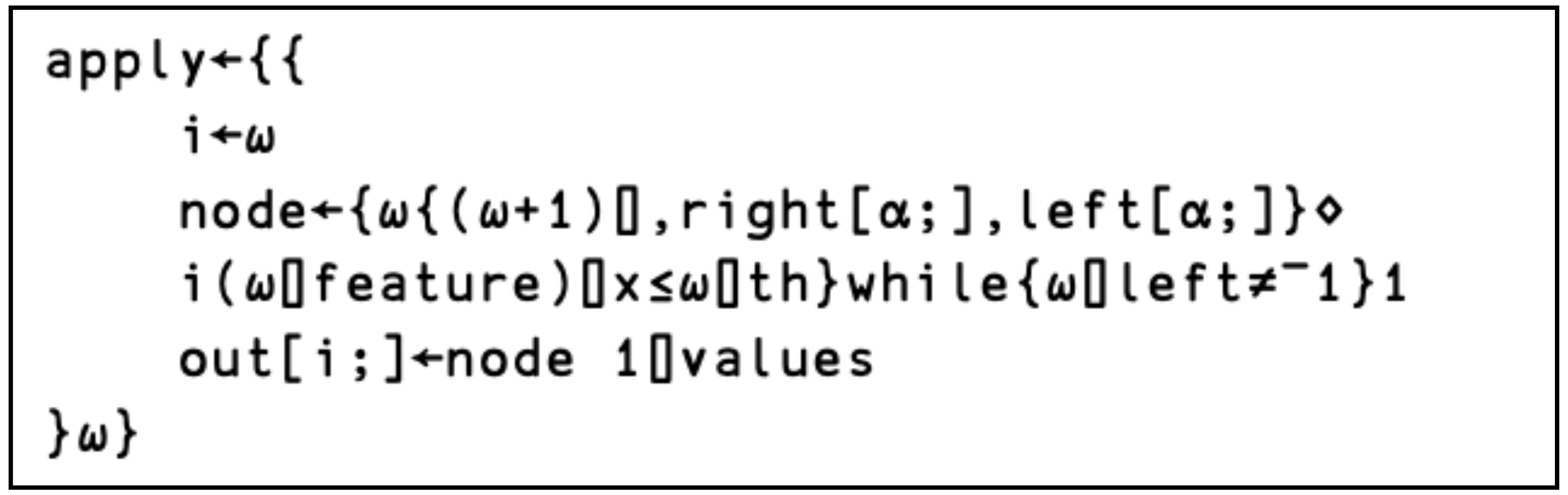

```
apply←{{
    i←ω
    node←{ω{(ω+1)⌷,right[α;],left[α;]}⋄
    i(ω⌷feature)⌷x≤ω⌷th}while{ω⌷left≠¯1}1
    out[i;]←node 1⌷values
}ω}
```

My first APL program: random forest traversal

Case study: random forest prediction

Performance aspect

- Modelling of Python scikit with APL
- Translating APL to SPIR-V
- Running SPIR-V with Vulkan



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Random forest binary tree traversal in APL

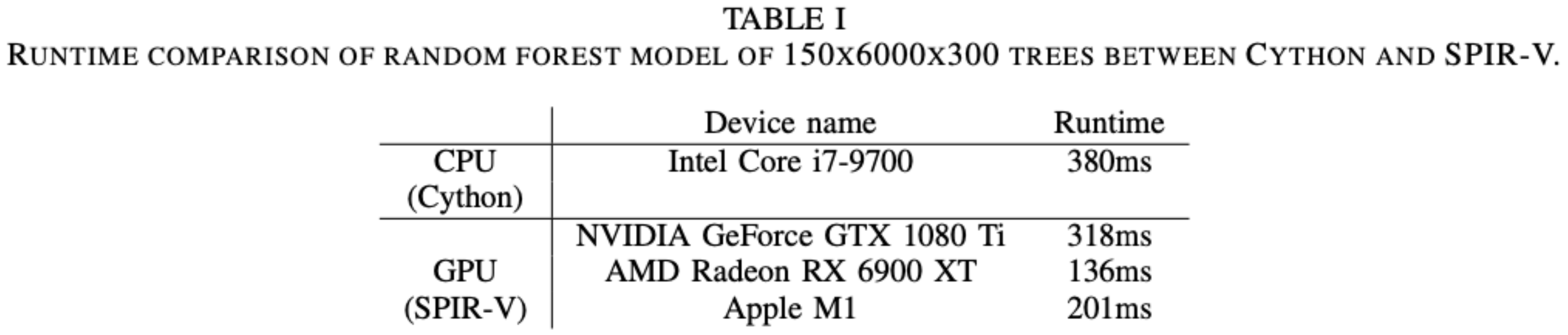


TABLE I
RUNTIME COMPARISON OF RANDOM FOREST MODEL OF 150X6000X300 TREES BETWEEN CYTHON AND SPIR-V.

	Device name	Runtime
CPU (Cython)	Intel Core i7-9700	380ms
GPU (SPIR-V)	NVIDIA GeForce GTX 1080 Ti	318ms
	AMD Radeon RX 6900 XT	136ms
	Apple M1	201ms

Results for small programs, memory copying remains the big bottleneck

Findings from the GPU world

- **what we compute**: APL programmers already think about data in a way that multi-core devices would want all programmers to think
- **how we compute**: machine-solvable drudgery that builds on top of the data representation
- **challenge**: how do we automate the **how**?

APL x Academics

Hot topics:

- **static rank polymorphism** (Remora @ Northeastern, Futhark @ Copenhagen, Dex @ Google)
- application area of **dependent types** (Idris @ St Andrews, Granule @ Kent)
- functional programming for **tensor computation** (Halide @ MIT / Adobe)
- an approach to simplify **parallel computation** (CUDA & Legate @ Nvidia, Matlab, Julia, Numpy, TensorFlow … etc. machine learning applications)

Software bugs
and where to find them

- main challenge: **recursion**
- at distance (i.e., abstractly) the waterfall makes no sense...
- ... but software will not realize something is wrong, unless we define **constraints** which describe how to build a waterfall
- => the need for **abstract interpretation**

Waterfal (Escher, 1961)

Types remove ambiguity

How problematic recursion can be caught

- types may express, **ownership**, **direction**, **multiplicities**

- linear types express **ownership**
  Finnish “koiran” - “dog’s”

- dependent types express **direction**
  Finnish “koirastani” - “from my dog”

- quantitative types tie **multiplicity** into ownership
  Finnish “koirillanikin” - “(something) that also my dogs have”

Typed waterfall

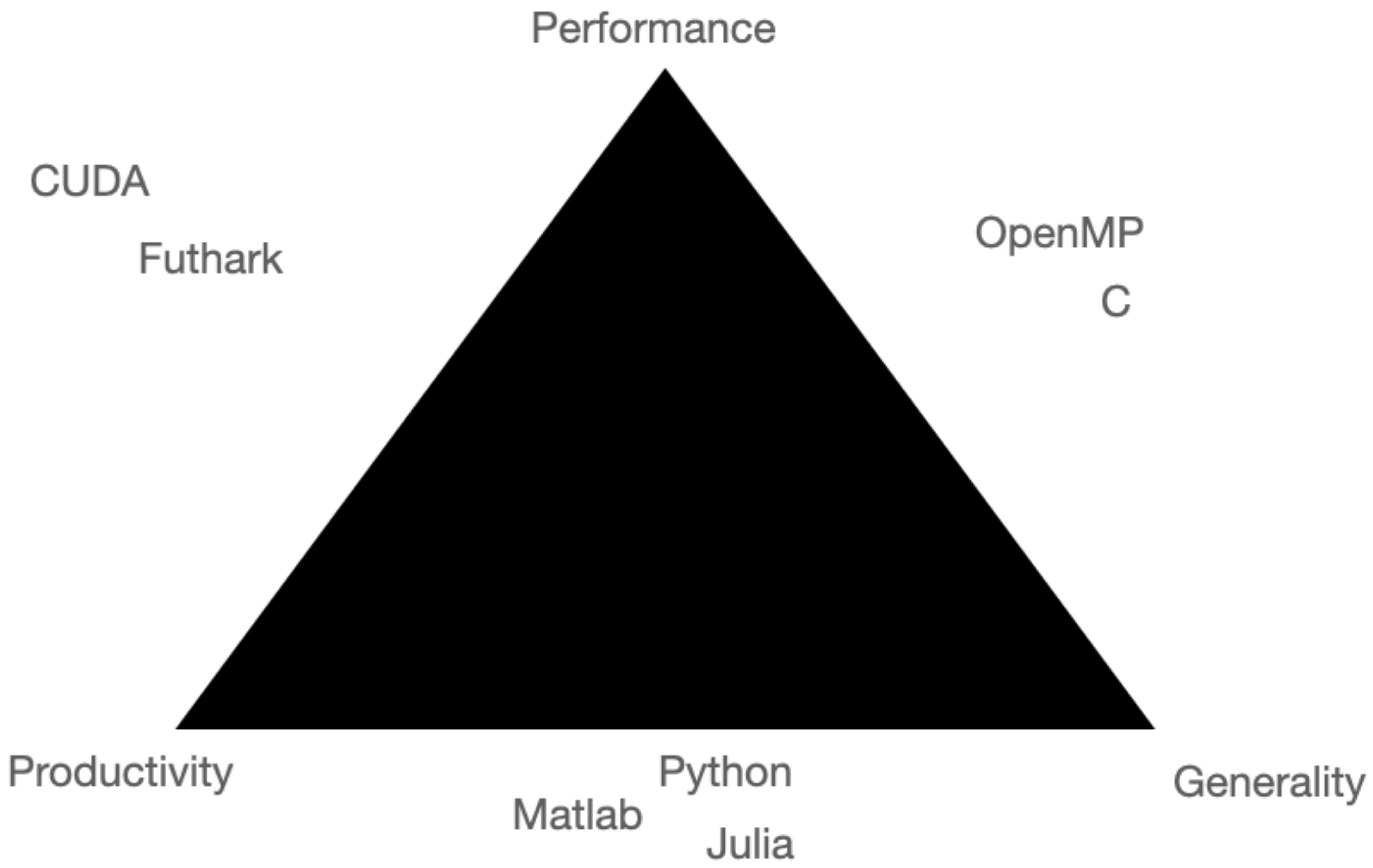
- types may express, **ownership**, **direction**, **multiplicities**

- what is the direction of the water?
- where does the water come from?
- can the water be re-used?
- answering these questions **constraints** the ways that a waterfall may be built
- constraints are **guides** in an otherwise random search for a solution

Waterfal (Escher, 1961)

Types are changing
… but so are computers

The Language Trilemma



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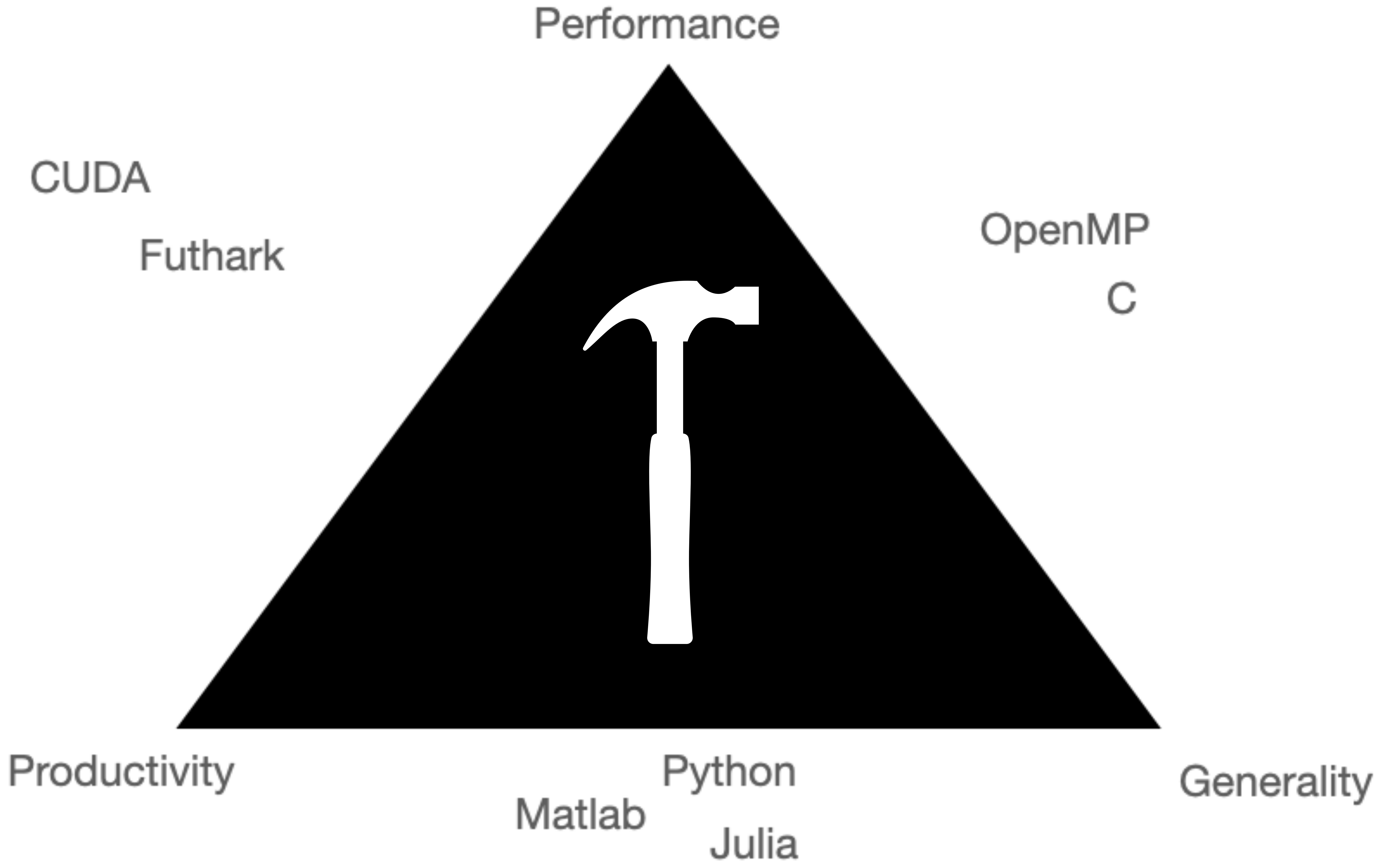

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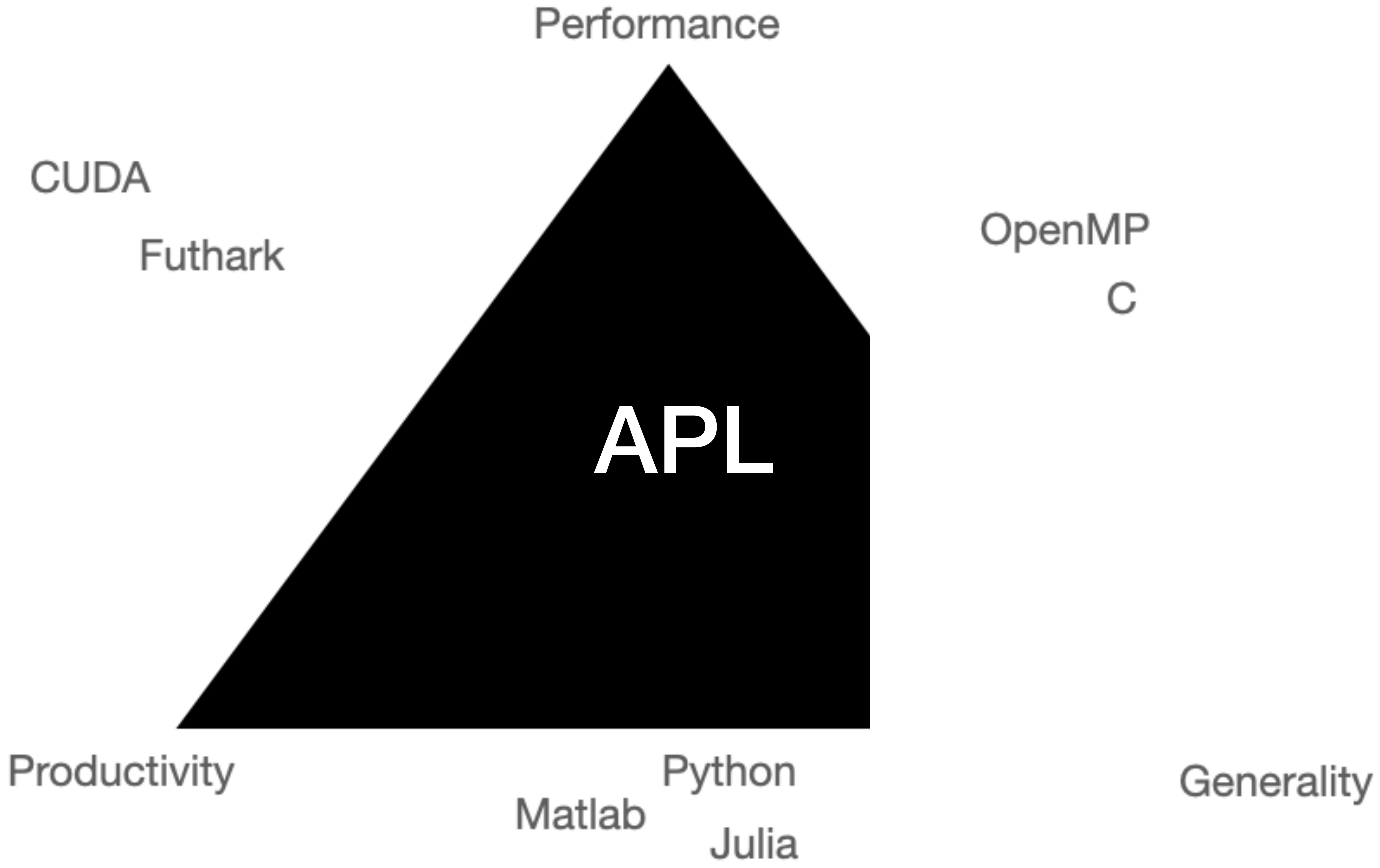


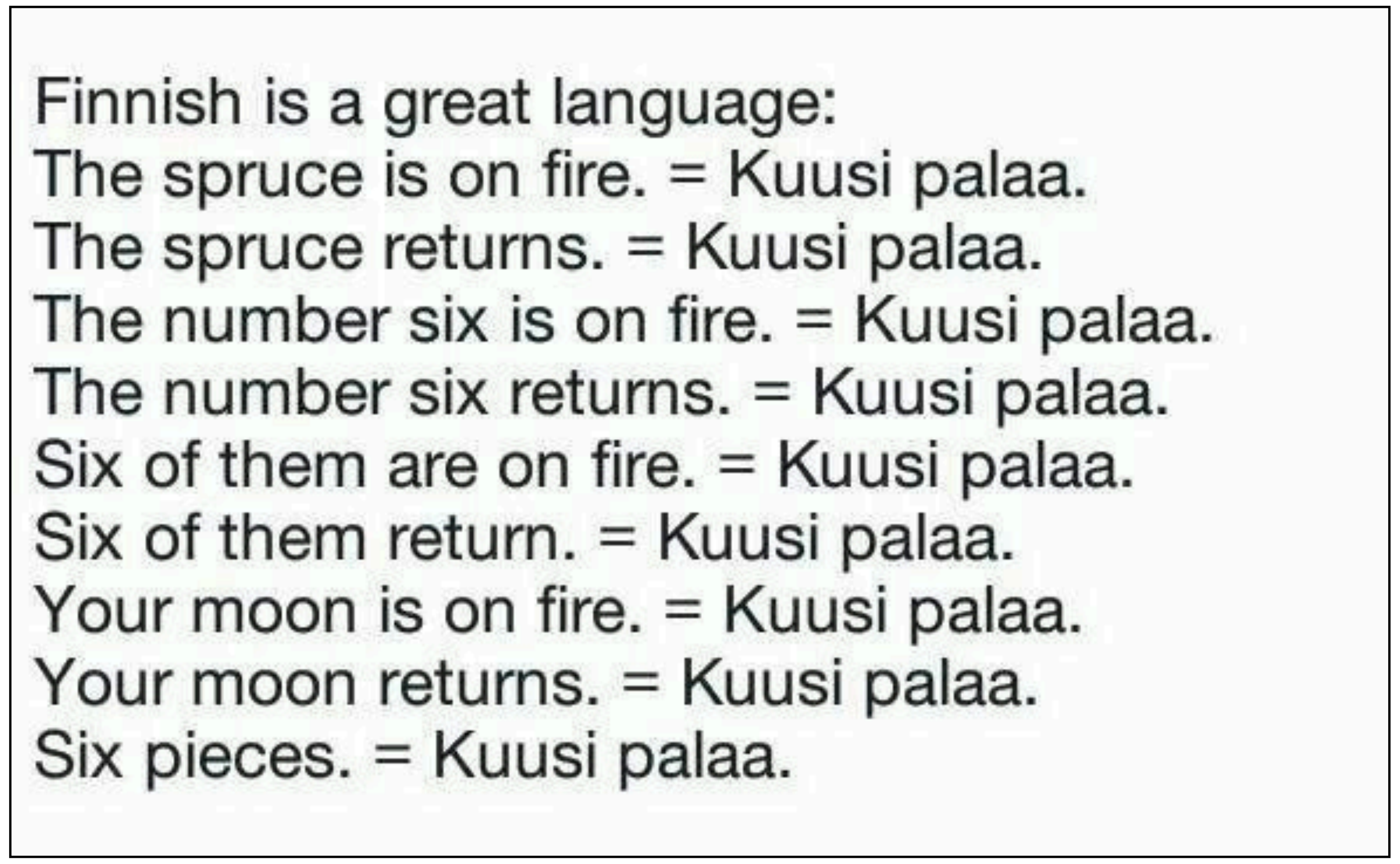
Q: What can we gain by losing generality?

A: Static rank polymorphism

- static semantics
- - "abstract interpretation"
- - what can we know before we start a program

- rank polymorphism
- - adds value-based "context" to the language interpretation

Gödel's incompleteness theorem: it is hard to interpret even simple programs



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A certain kind of rank polymorphism in action

Q: Why is static rank polymorphism useful?

A: It simplifies *Parallel Programming*

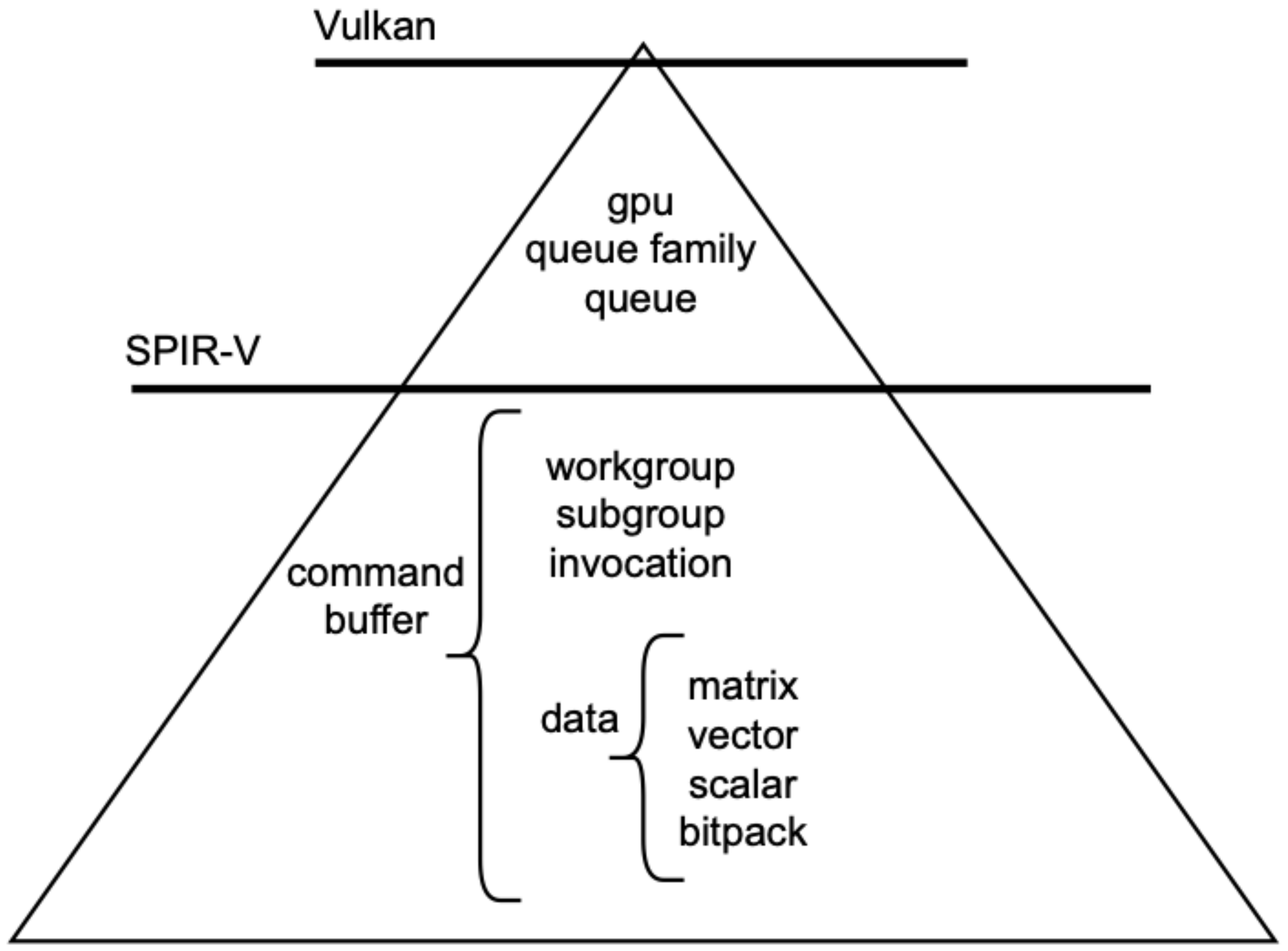
- Accumulators 👎
  divide-and-conquer 👍
- However, dividing and conquering is hard when you don't know the amount of "troops"
- Remark: array programming languages abstract away the execution strategy

GPU	Subgroup size	Queue families	Queue lengths
Intel	8/16/32	?	?
AMD	64	3	16/8/1
Nvidia	32	3	16/8/1
Adreno	64	?	?
Mali	16	?	?
Apple M1	32	4	1/1/1/1

Varying "troops" on GPUs => need for dynamic scheduling

Putting it together

- Challenge: understanding what **shapes** data may have
- Needed for: **constraints** which build the rest of the pyramid for us
- => can be achieved with shape analysis by employing new type systems
- “the APL way” remains — data-driven, no unnecessary software ceremonies



Shape analysis

To always know how many “troops” we have!

- practicality
- - typing for GPUs: strong typing facilitates work splitting — efficiency
- - background: nice to have a single program work for any GPU

- theoretical
- - advanced type system applications: what can we know beforehand
- - array programming: how can we generalize, adapt the information

Parallelism is much easier with abstract interpretation (“knowing your troops”)

Scheduling Array Operations

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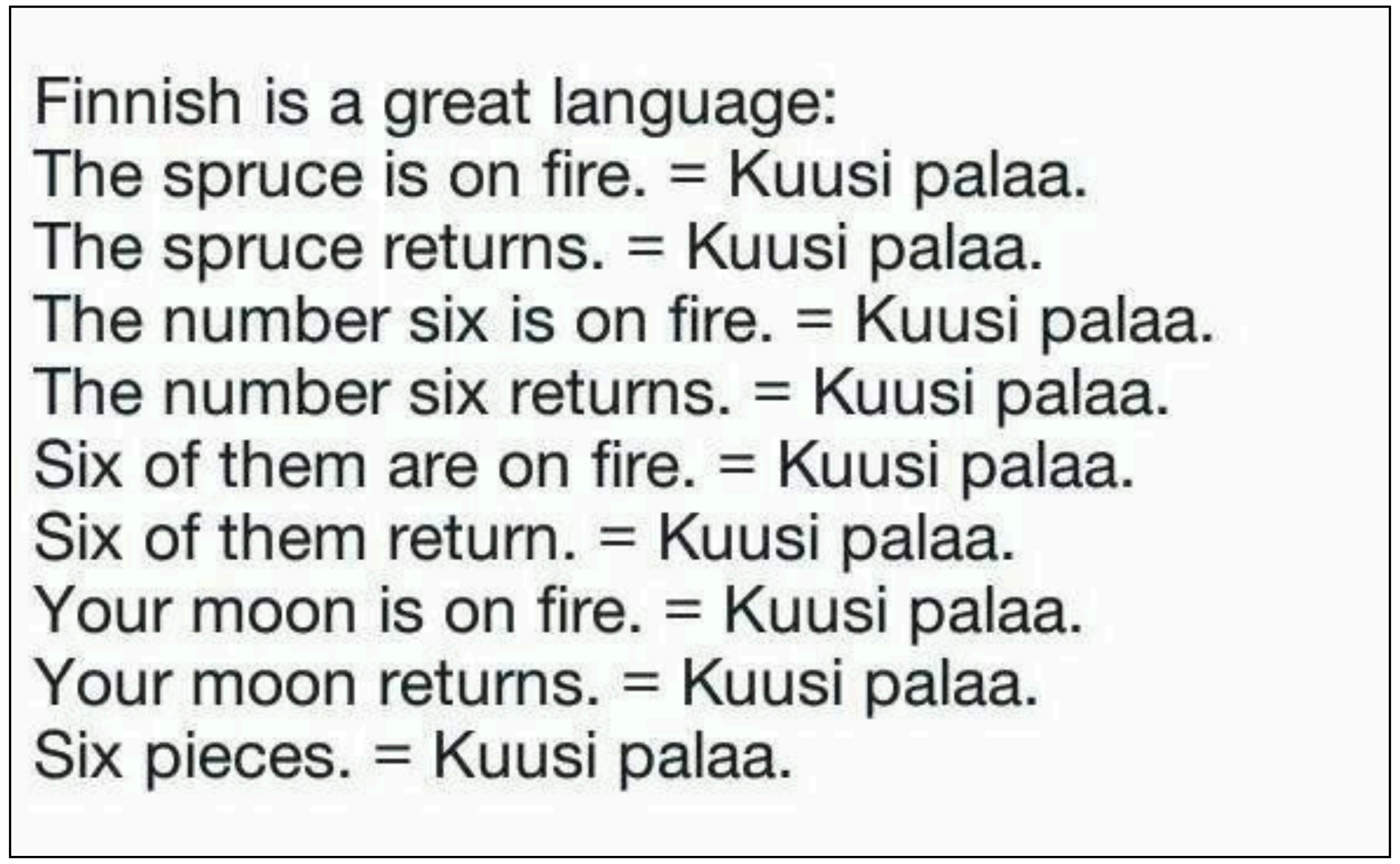
Challenge: building connection between static semantics



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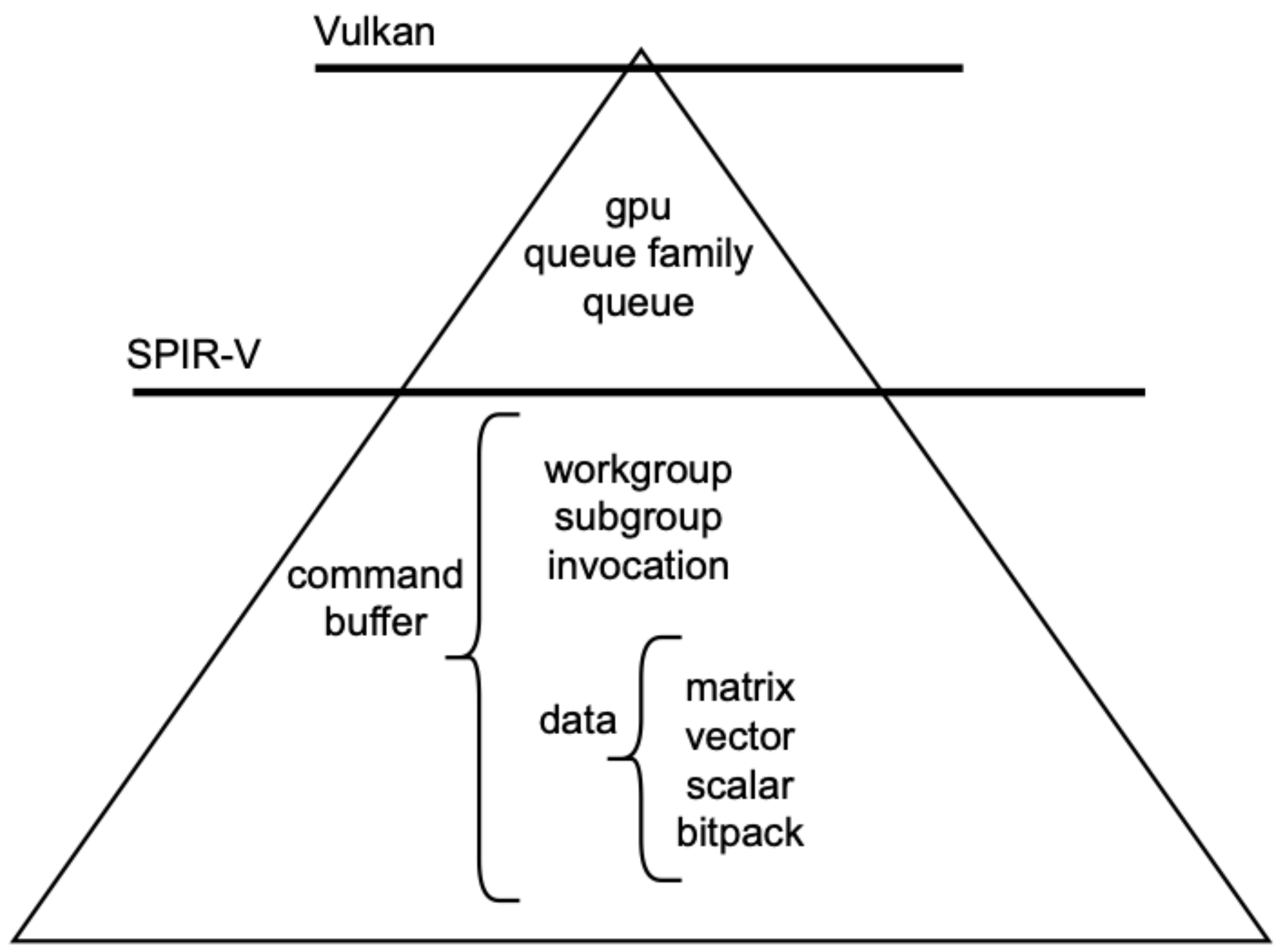

Hierarchy of GPU

Takeaway

- APLers already think in the way that new hardware wants us to …
- … however, the languages must "see" things like APLers do
- => types can help the computer to constrain, search its way out to "see"
- => this way, the types build **on top** of the APL arrays

- **let the types work for us, not the other way around**
- => performance optimizations on multi-core systems, such as GPUs (SIMD use)
- => automatic distribution (divide and conquer strategies)

Questions?