Imperial College London

LSDS Large-Scale Distributed Systems Group

Designing Hybrid Data Processing Systems for Heterogeneous Servers

Peter Pietzuch

Large-Scale Distributed Systems (LSDS) Group
Imperial College London

http://lsds.doc.ic.ac.uk
<prp@imperial.ac.uk>

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Data is the New Oil

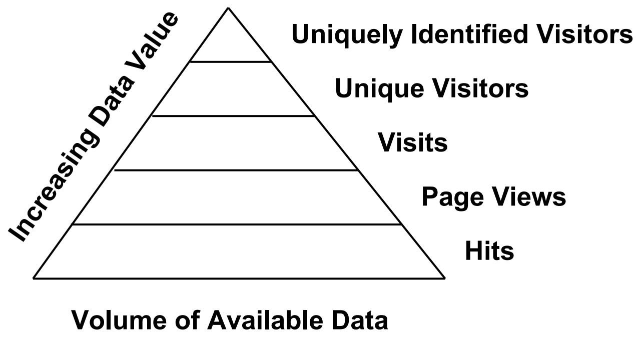
Many new **sources of data** become available
- Most data is produced continuously

Data powers plethora of **new and personalised services**…

Data-Intensive Systems

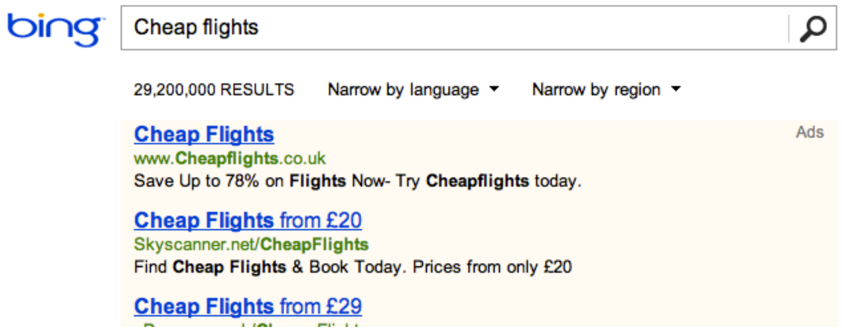
Data analytics over web click streams

- How to maximise user experience with relevant content?
- How to analyse "click paths" to trace most common user routes?



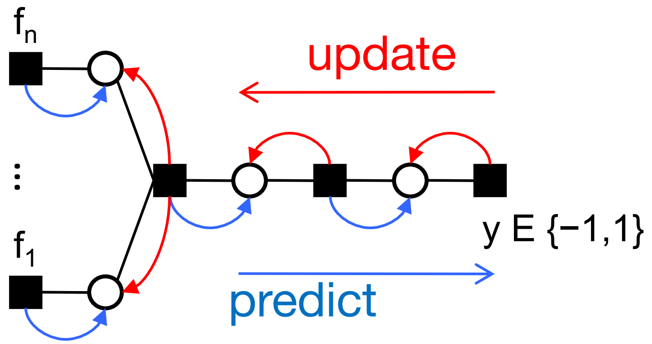
Machine learning models for online prediction

- E.g. serving adverts on search engines

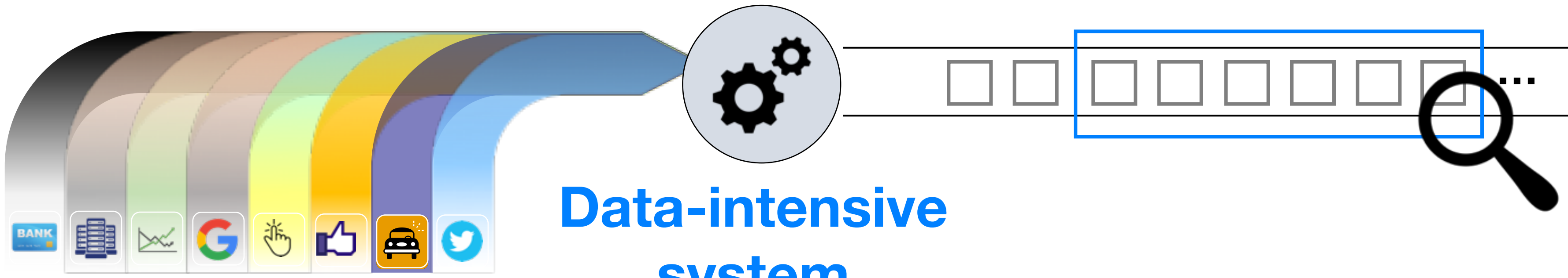


Solution: **AdPredictor**

- Bayesian learning algorithm ranks adverts according to click probabilities



Throughout and Result Freshness Matter



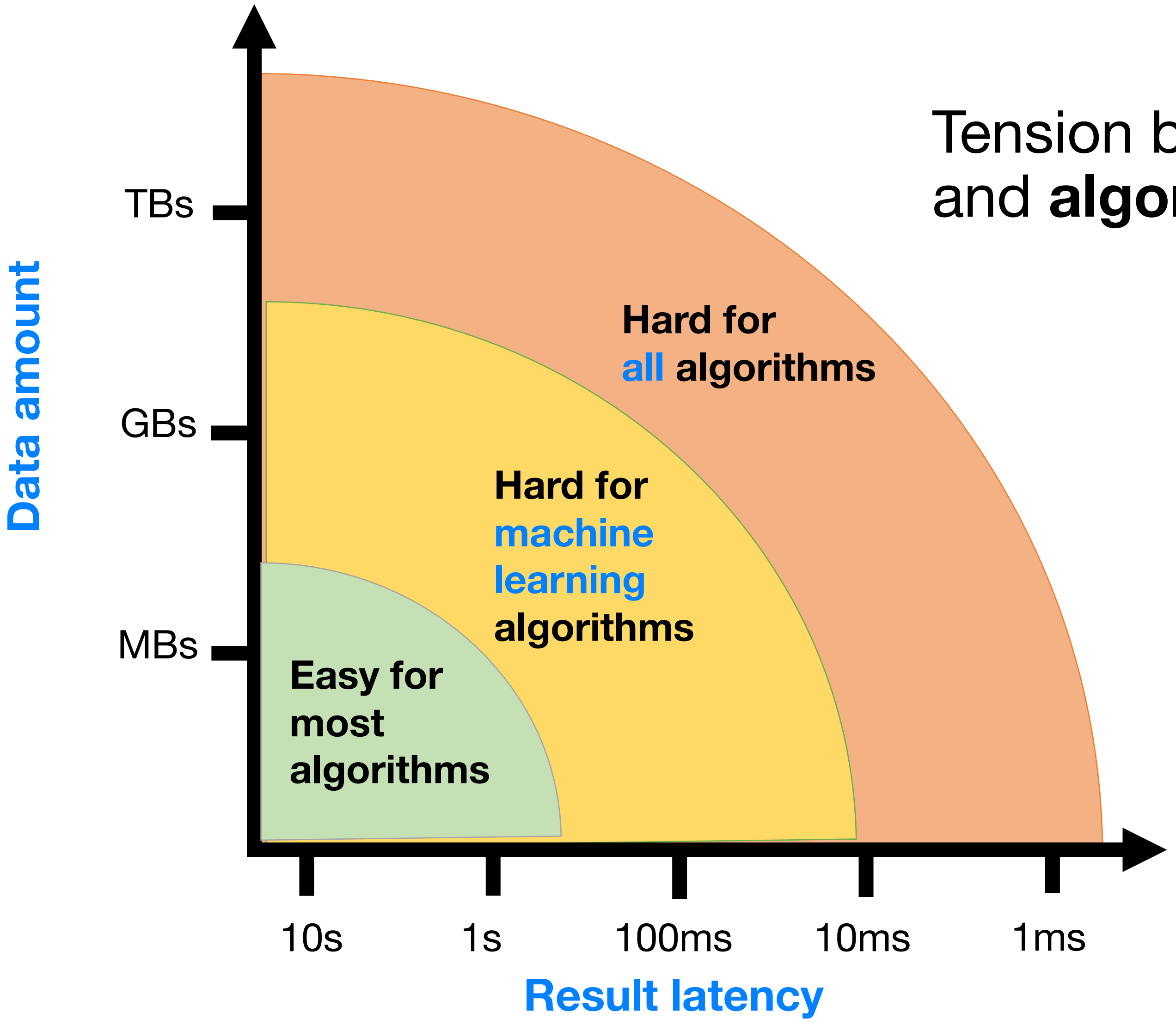
Data-intensive system

High-throughput processing

Low-latency results

Facebook Insights:	**Aggregates 9 GB/s**	**< 10 sec latency**
Feedzai:	**40K credit card transactions/s**	**< 25 ms latency**
Google Zeitgeist:	**40K user queries/s**	**< 1 ms latency**
NovaSparks:	**150M trade options/s**	**< 1 ms latency**

Design Space for Data-Intensive Systems



Tension between **performance** and **algorithmic complexity**

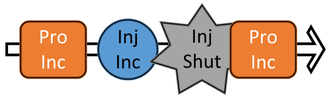
Algorithmic Complexity Increases

T1
T2
T3

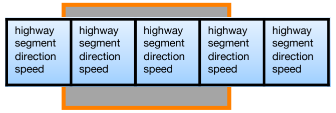
Topic-based filtering

T1(a, b, c)
T2(c, d, e)
T3(g, i, h)

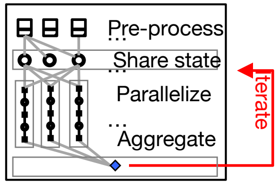
Content-based filtering



Complex pattern matching



Stream queries



Online machine learning, data mining

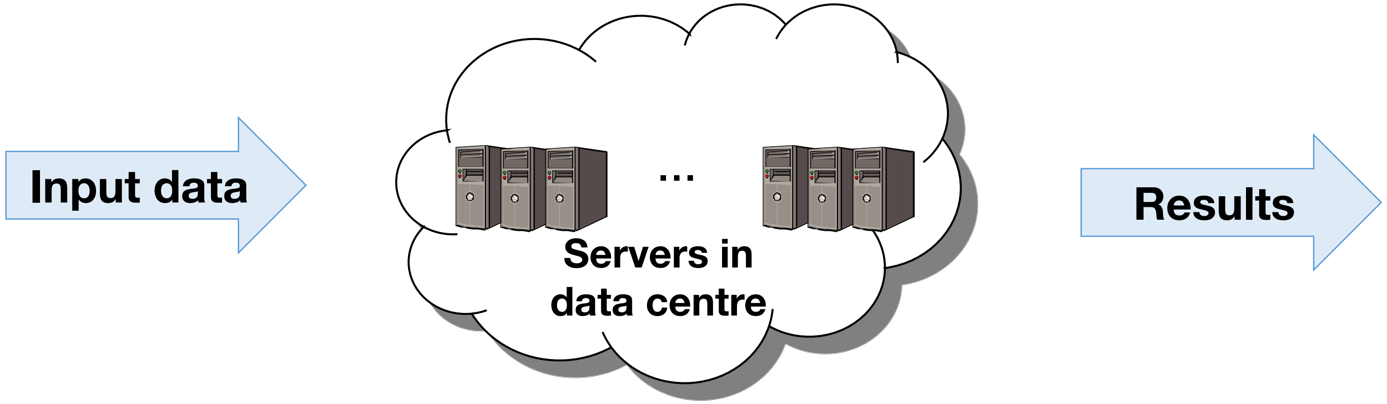
Publish/Subscribe

Complex Event Processing (CEP)

Stream processing

Scale Out Model in Data Centres

Task Parallelism vs. Data Parallelism



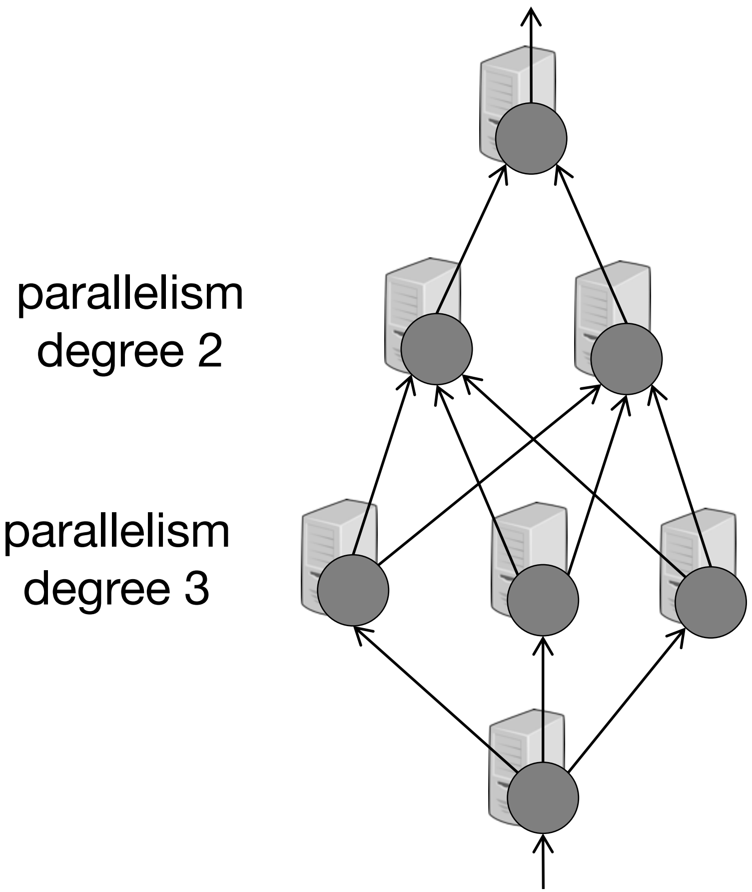

```
select highway, segment, direction, AVG(speed)
from Vehicles[range 5 seconds slide 1 second]
group by    highway, segment, direction
having      avg < 40
```

Task parallelism:
Multiple data processing jobs

```
select highway, segment, direction, AVG(speed)
from Vehicles[range 5 seconds slide 1 second]
group by    highway, segment, direction
having      avg < 40
```

Data parallelism:
Single data processing job

Distributed Dataflow Systems



Idea:
Execute **data-parallel tasks**
on cluster nodes

Tasks organised as **dataflow graph**

Almost all big data systems do this:

Apache Hadoop, Apache Spark,
Apache Storm, Apache Flink,
Google TensorFlow, ...

Nobody Ever Got Fired For Using Hadoop/Spark

2012 study of **MapReduce** workloads

(A. Rowstron, D. Narayanan, A. Donnely, G. O'Shea, A. Douglas, HotCDP'12)

- Microsoft: median job size **< 14 GB**
- Yahoo: median job size **< 12.5 GB**
- Facebook: 90% of jobs **< 100 GB**

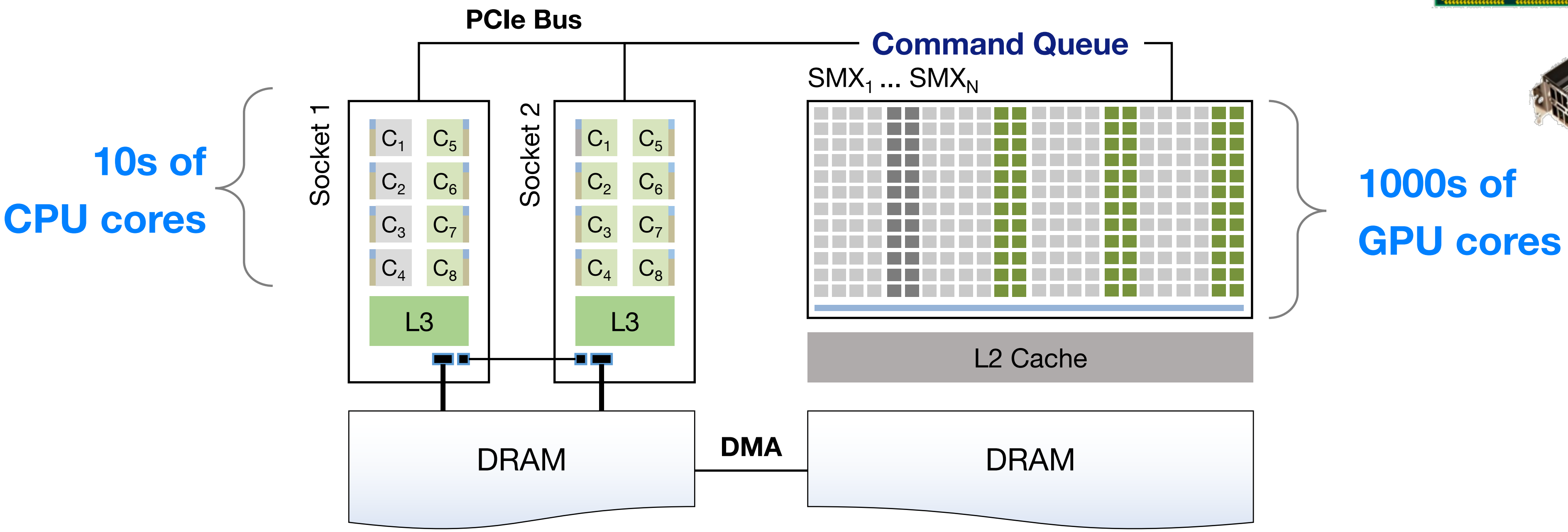
Many data-intensive jobs easily fit into **memory**

One server cheaper/more efficient than **compute cluster**

Parallelism of Heterogeneous Servers

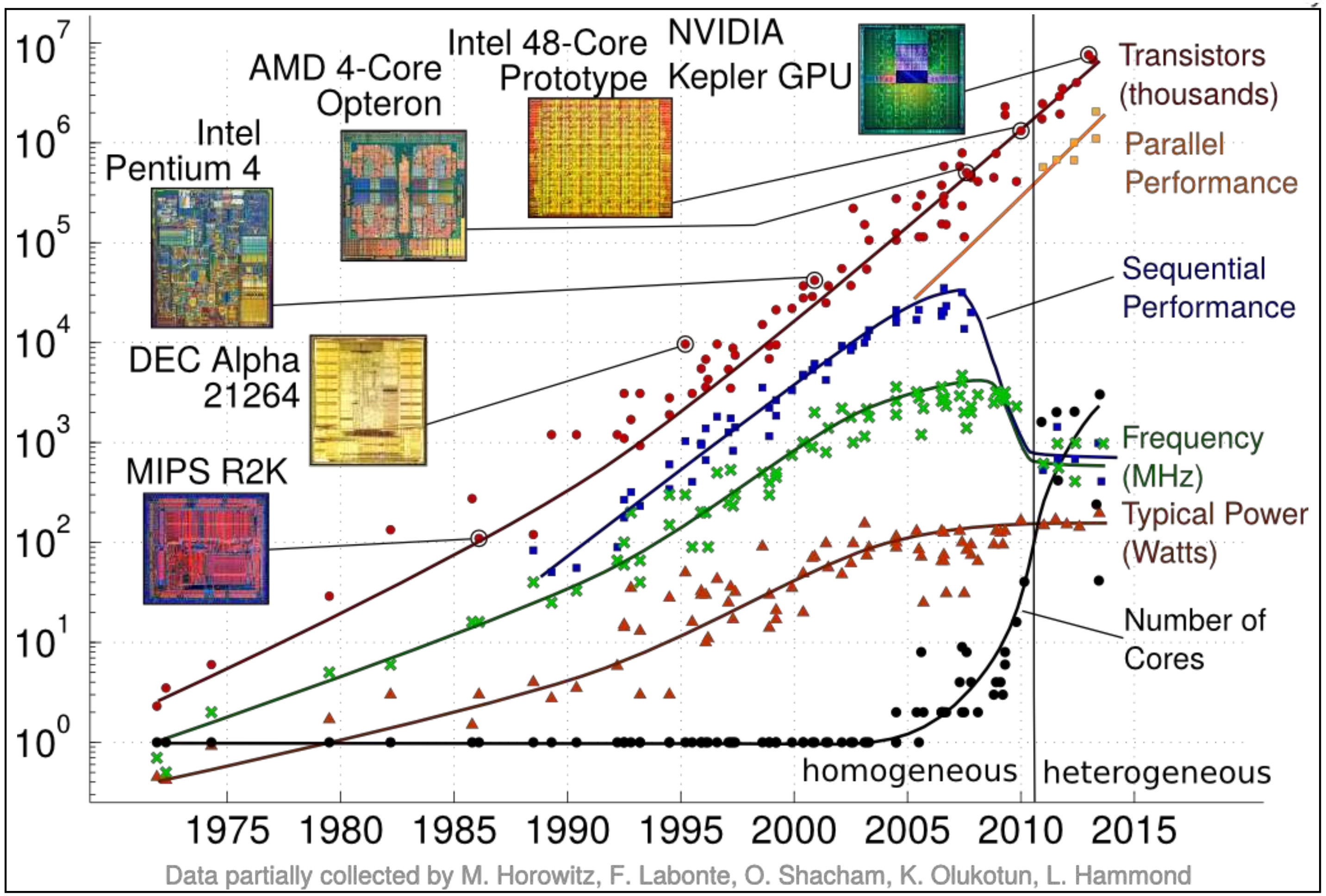
Servers have many parallel **CPU cores**

Heterogeneous servers with **GPUs** common



New types of **compute accelerators:** Xeon Phi, Google's TPUs, FPGAs, ...

Servers Are Becoming Increasingly Heterogeneous



Slide courtesy of Torsten Hoefler (Systems Group, ETH Zürich)

☛ **How can Data-Intensive Systems Exploit Heterogeneous Hardware?**

Roadmap

SABER: Hybrid stream processing engine for heterogeneous servers

[SIGMOD'16]

(1) How to **parallelise computation** on modern hardware?

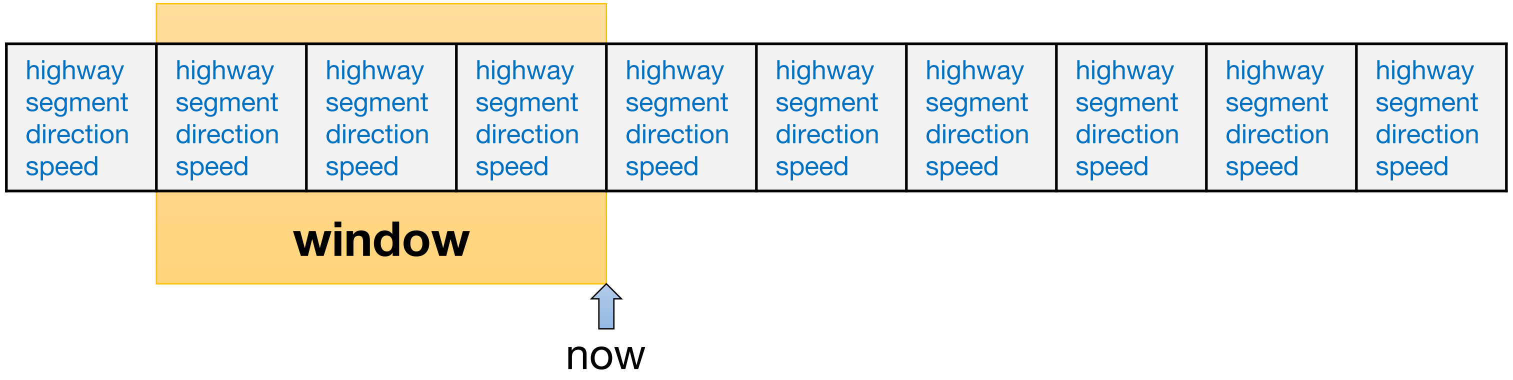
(2) How to utilise **heterogeneous servers**?

(3) Experimental **performance results**

Analytics with Window-based Stream Queries

Real-time analytics over data streams

Windows define **finite data amount** for processing



Time-based window with size τ at current time t

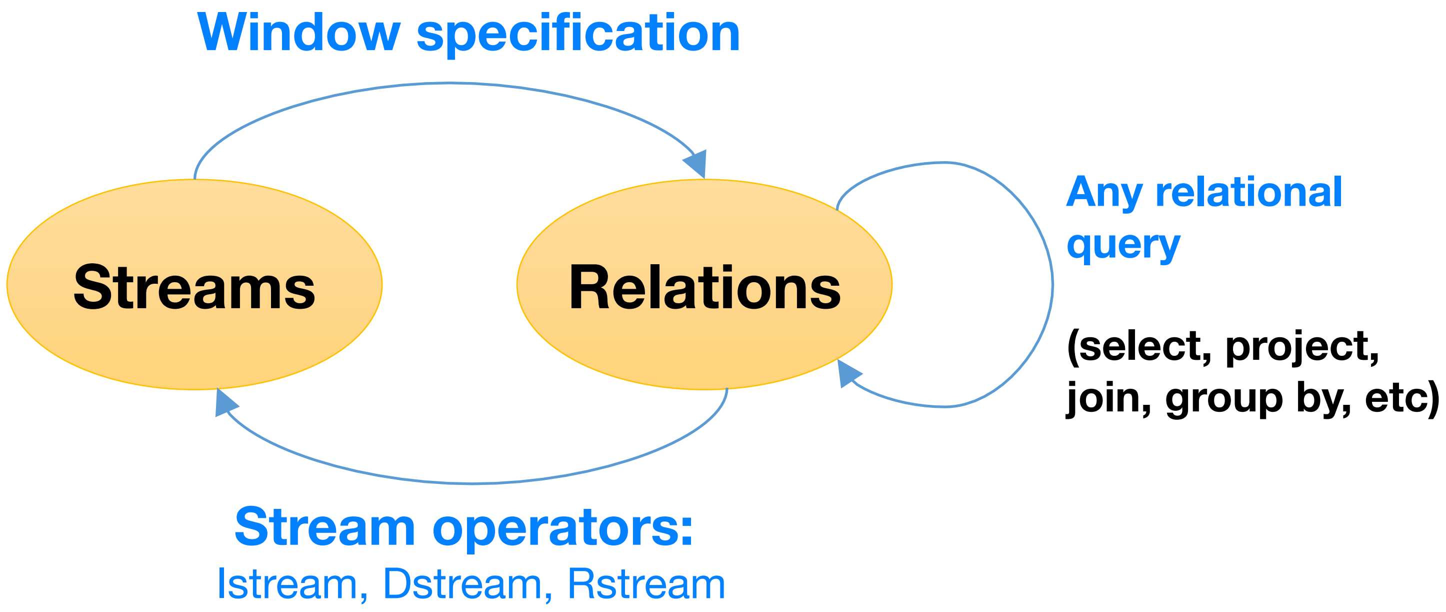
[t - τ : t] Vehicles[Range τ seconds]

Count-based window with size n:

last n tuples Vehicles[Rows n]

Defining Stream Query Semantics

Windows convert **data streams** to **dynamic relations** (database table)



SQL Stream Queries

SQL provides well-defined declarative semantics for queries

- Based on relational algebra (select, project, join, …)

Example: Identify slow moving traffic on highway

- Input stream: Vehicles(highway, segment, direction, speed)
- Find highway segments with average speed below 40 km/h

```
select      highway, segment,
            direction, AVG(speed) as avg
from        Vehicles[range 5 sec slide 1 sec]
group by    highway, segment, direction
having      avg < 40
```

Output

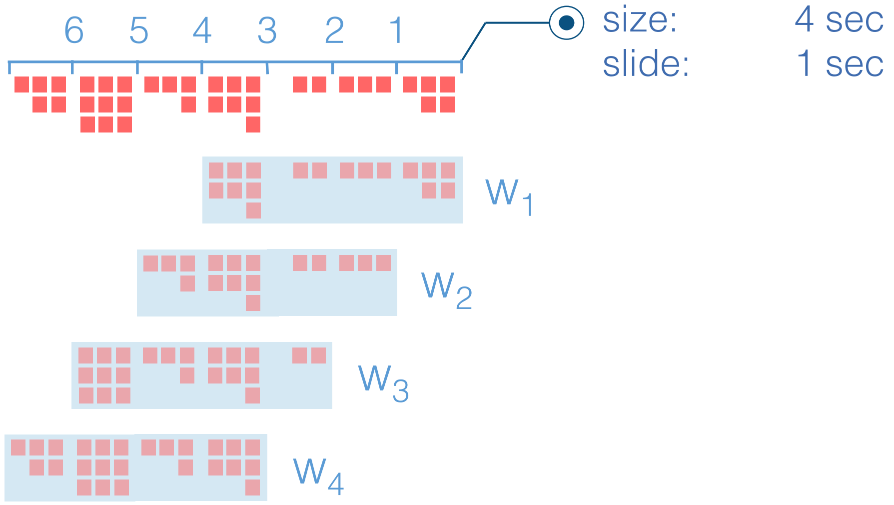
Input data

Operators

(1) How to Parallelise Computation?

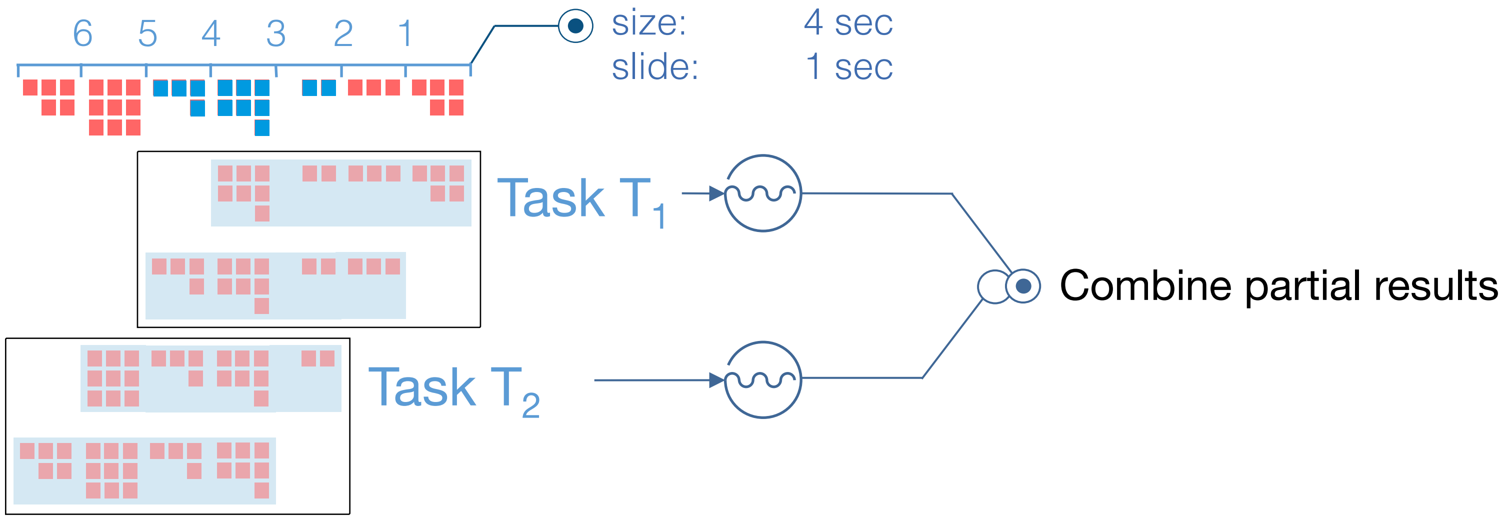
Perform query evaluation across **sliding windows** in **parallel**

- Exploit data parallelism across stream



How to use GPUs with Stream Queries?

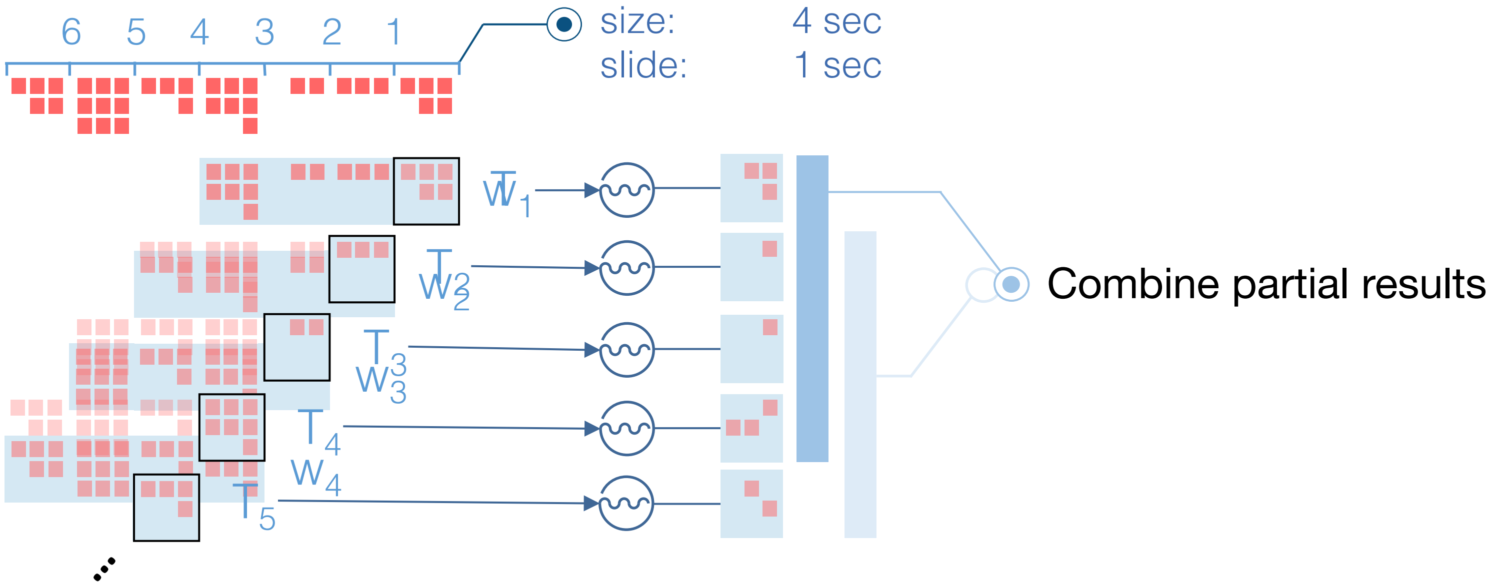
Naive strategy parallelises computation along **window** boundaries



☛ **Window-based** parallelism results in **redundant** computation

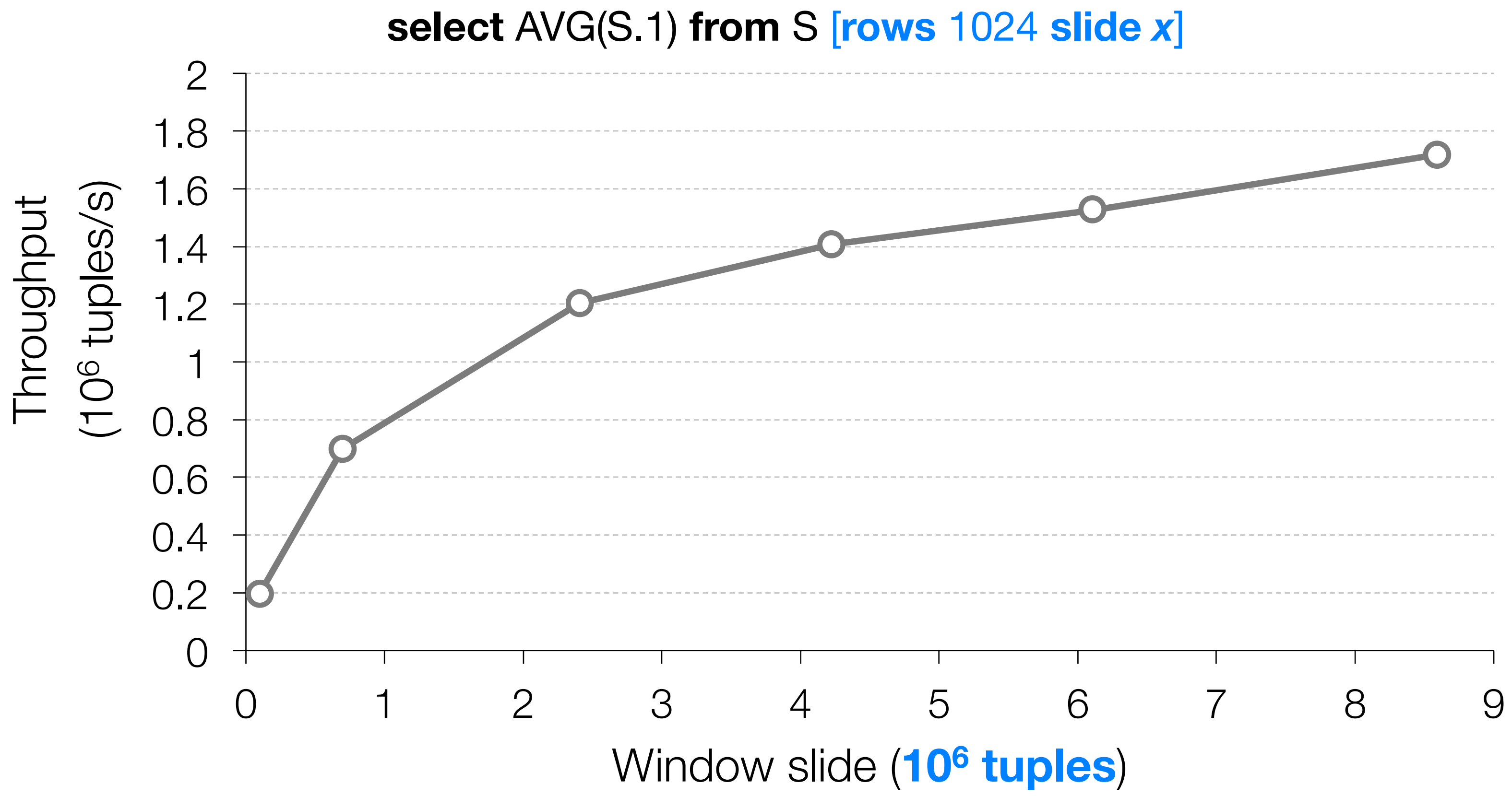
How to use GPUs with Stream Queries?

Parallel processing of **non-overlapping** window data?



☛ **Slide-based** parallelism limits degree of parallelism

Apache Spark: Small Slides → Low Throughput

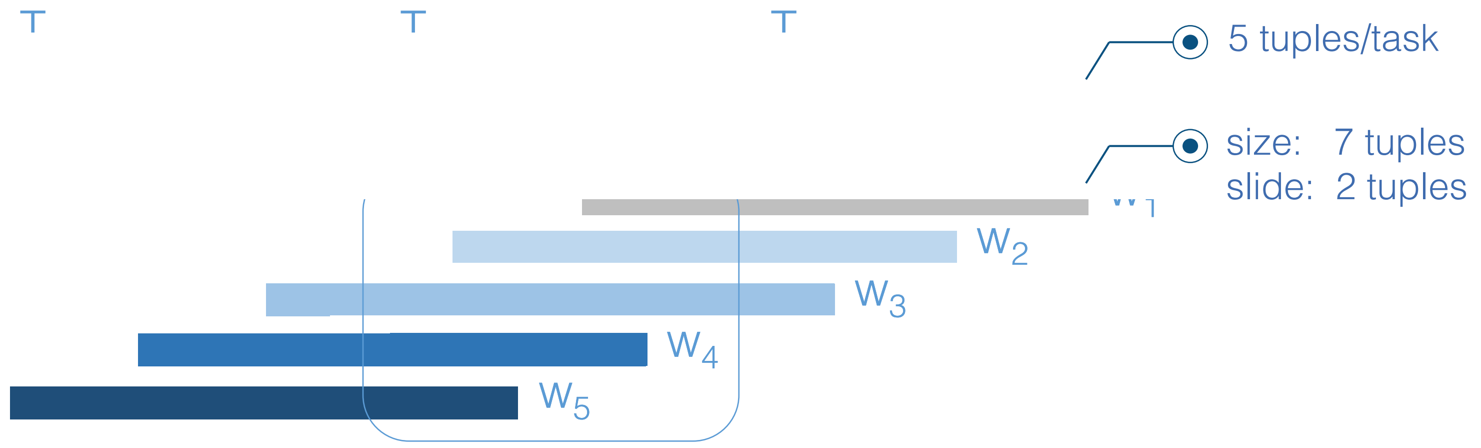


Spark relates **window slide** to **micro-batch size** used for parallelisation

☛ Avoid **coupling system parameters** with **query definition**

SABER: Parallel Window Processing

Idea: Parallelise using **task size** that is **best for hardware**

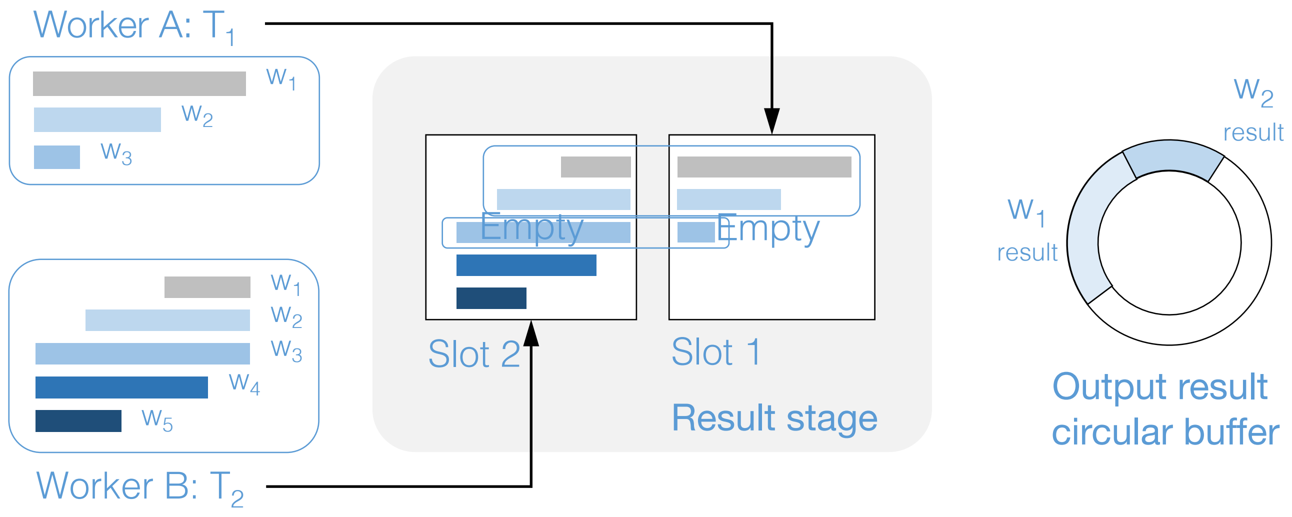


Task contains one or more window fragments

SABER: Window Fragment Processing

Process window fragments in parallel

Reassemble partial results to obtain **overall result**



Partial result reassembly must also be done in parallel

API for Operator Implementation

Fragment function f_f

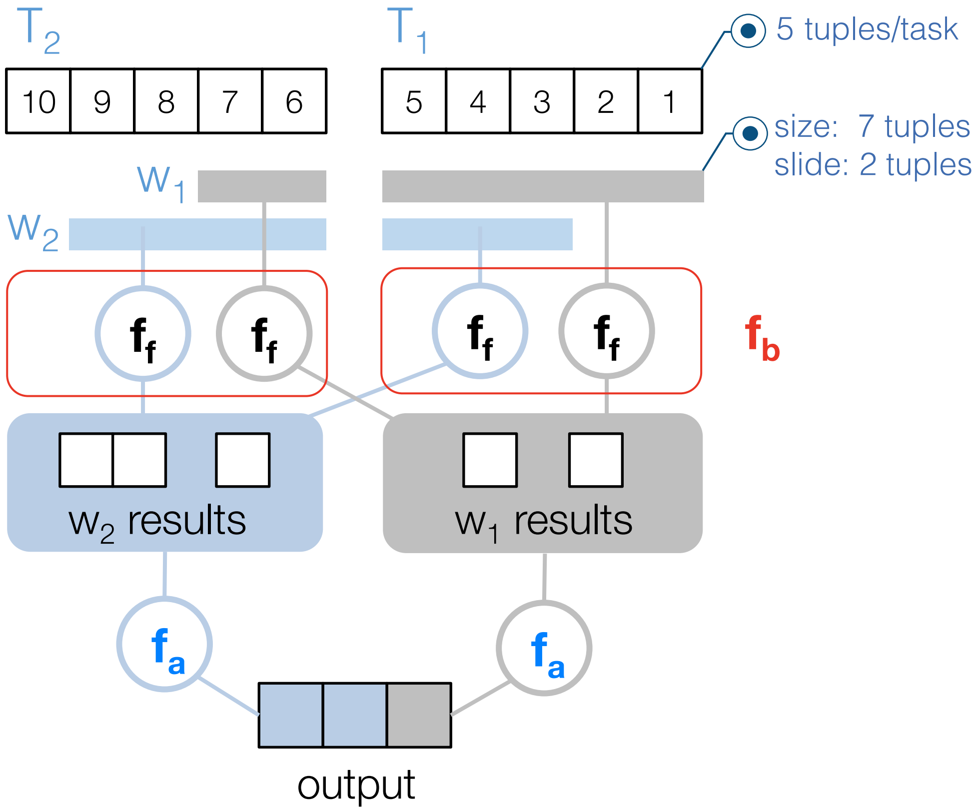
- Processes window fragments

Assembly function f_a

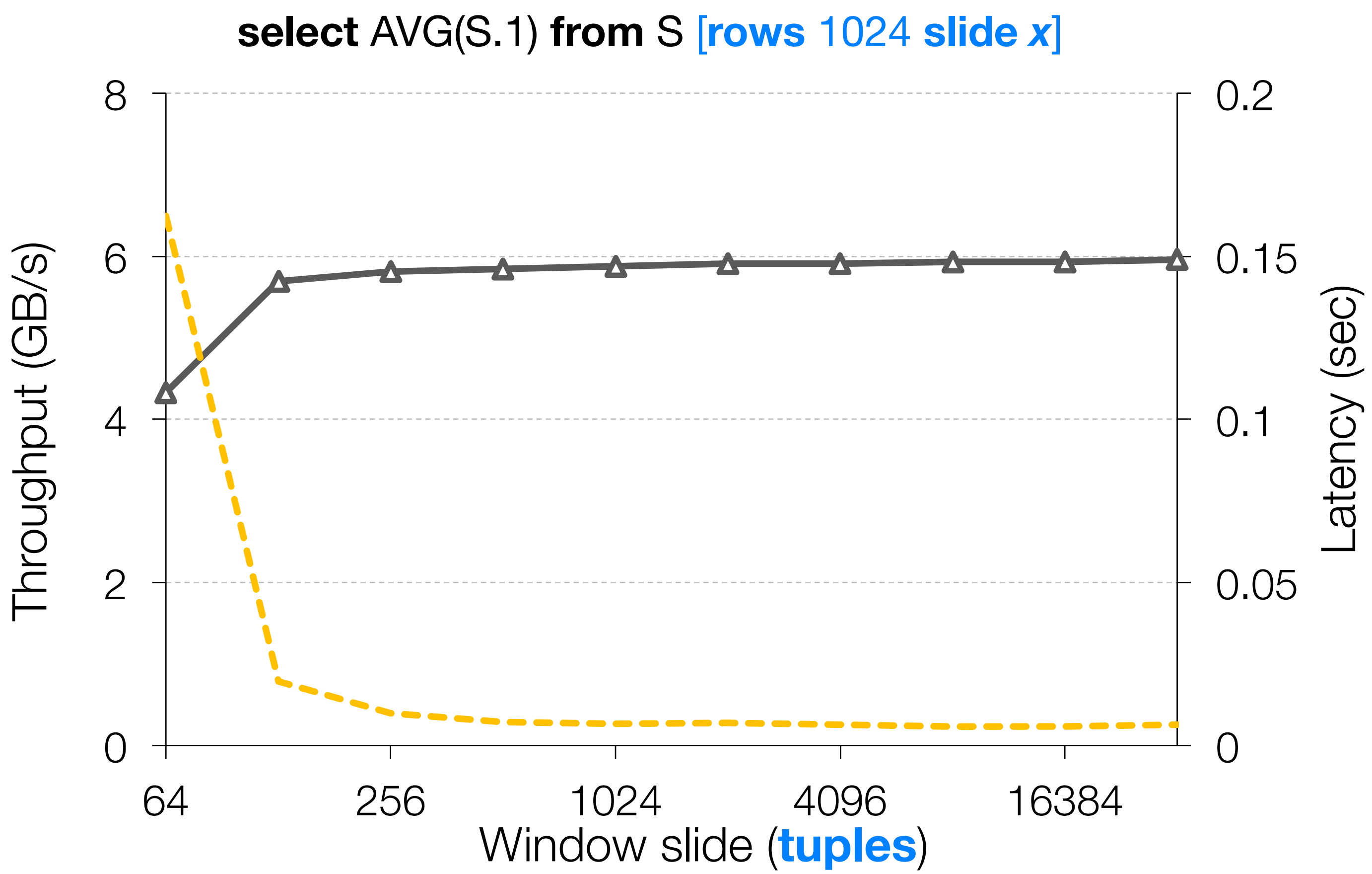
- Merges partial window results

Batch function f_b

- Composes fragment functions within task
- Allows incremental processing



SABER: Performance of Window-based Queries

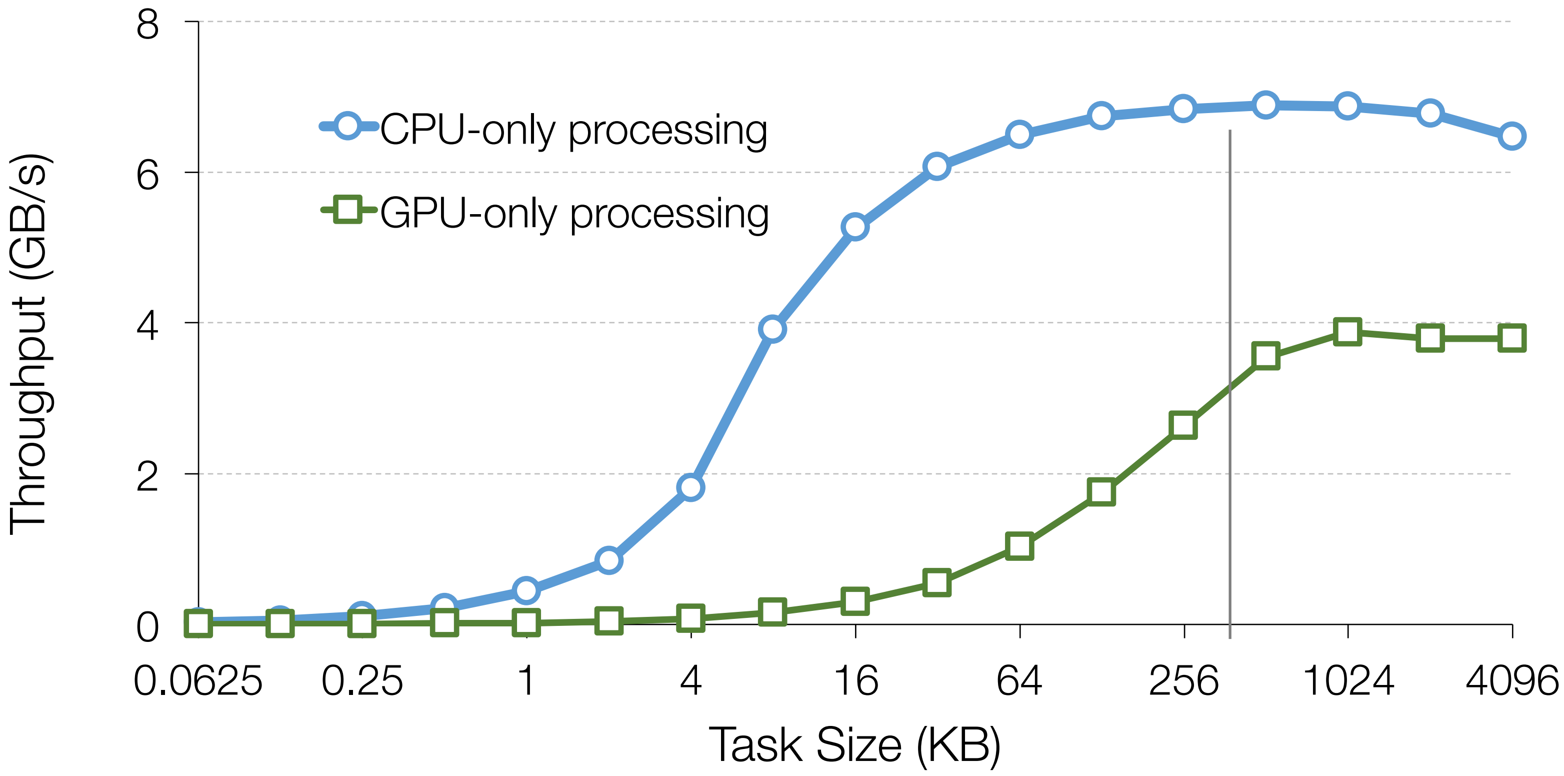


☛ **Performance** of **window-based queries** remains **predictable**

How to Pick the Task Size?

Problem: Small data transfers over PCIe bus costly

- Example: **select** * from S **where** p1 [rows 1 slide 1]



Limited by dispatcher and thread contention

Limited by data movement

Roadmap

SABER: Hybrid stream processing engine for heterogeneous servers

[SIGMOD'16]

(1) How to **parallelise computation** on modern hardware?

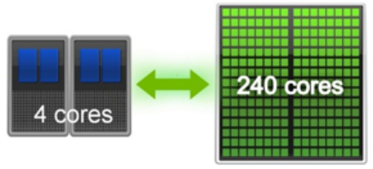
☛ Avoid coupling **system parameters** with **processing semantics**

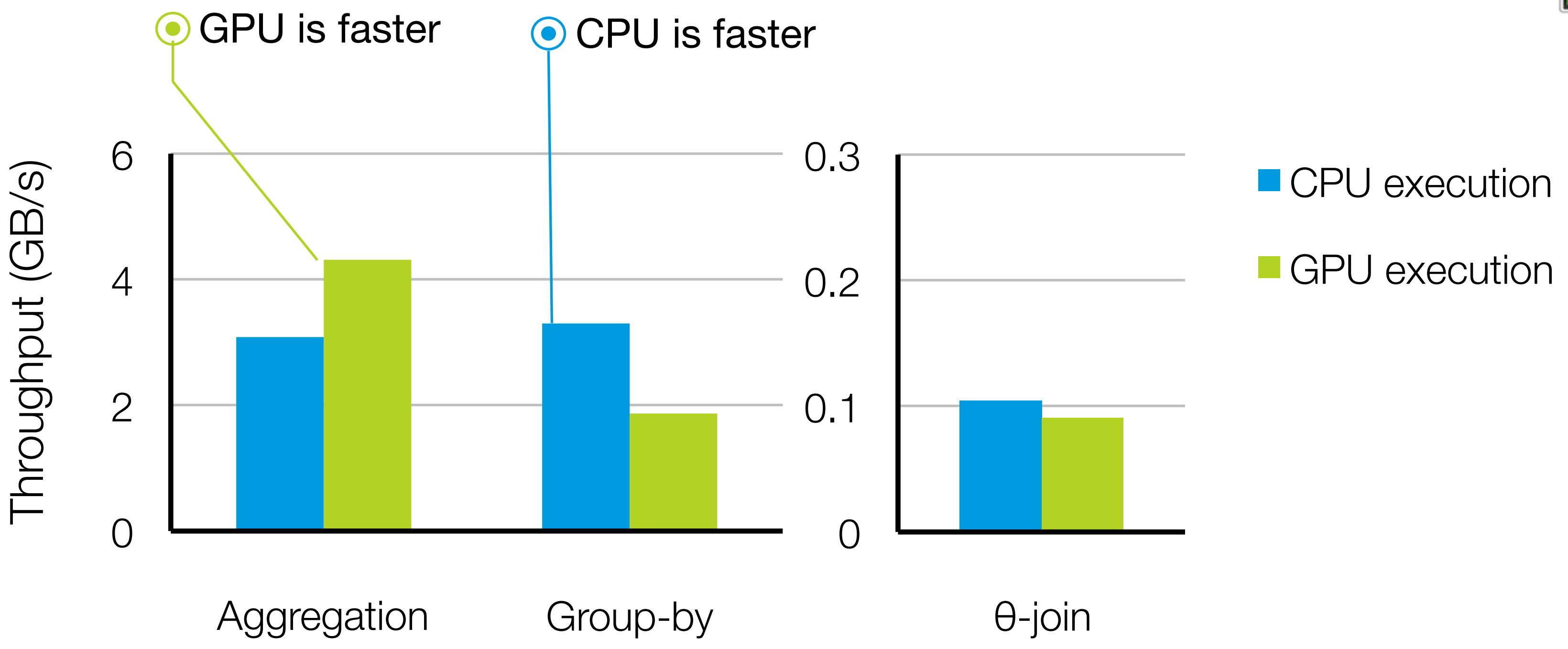
(2) How to utilise **heterogeneous servers**?

(2) How to Utilise Heterogeneous Servers?

Hard to decide **acceleration potential** of heterogeneous processors

– Depends on operator semantics, window definition, data distribution, …

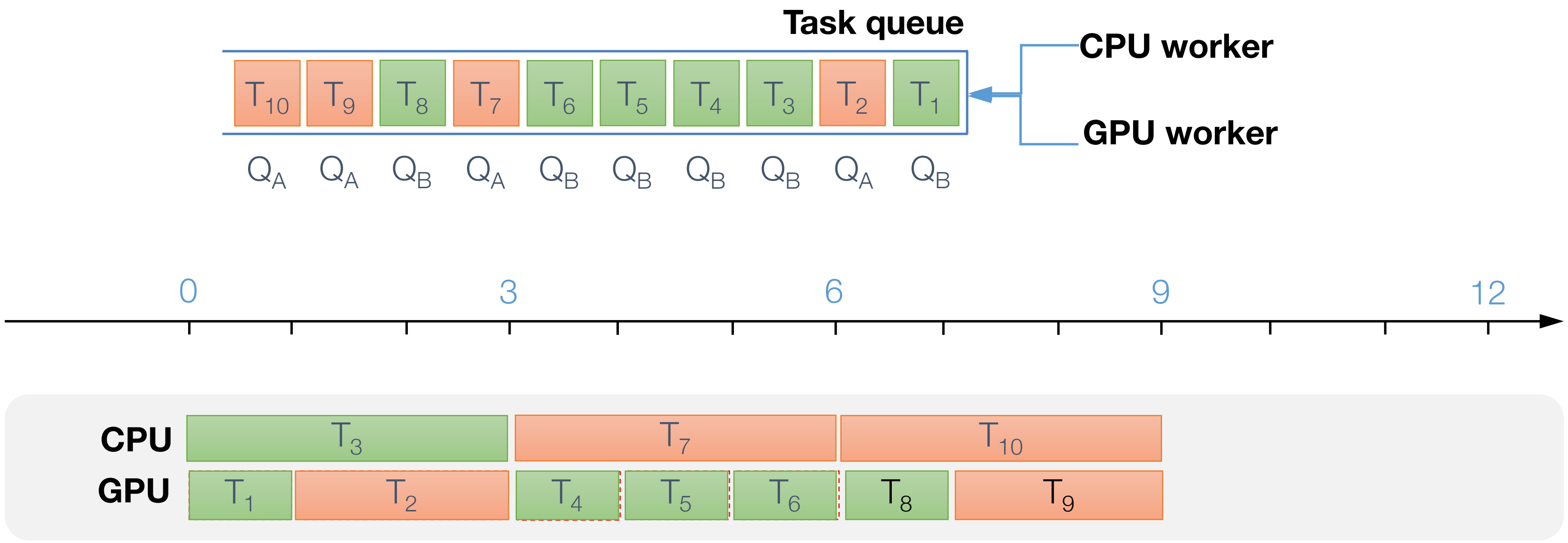




☛ Don’t leave decision about heterogeneous processors to users

SABER: Hybrid Execution Model

Idea: Execute tasks on **all heterogeneous processors** (CPUs, GPUs, ...)



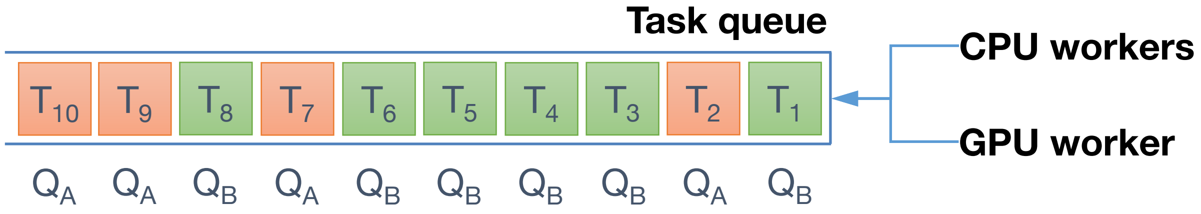
Fully utilise all hardware parallelism available in dedicated servers

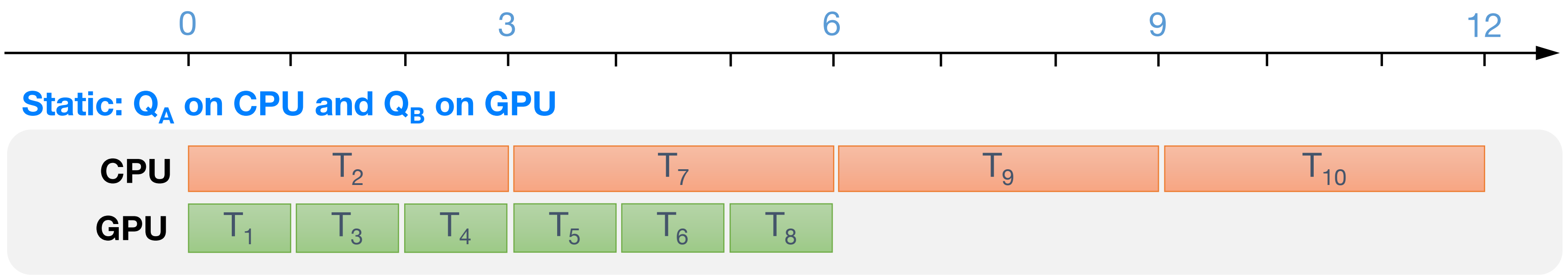
Static Task Scheduling using Cost Model?

Profile tasks to obtain cost model

Assign tasks to processor with **shortest execution time**

	CPU	GPU
Q_A	3 ms	**2 ms**
Q_B	3 ms	**1 ms**





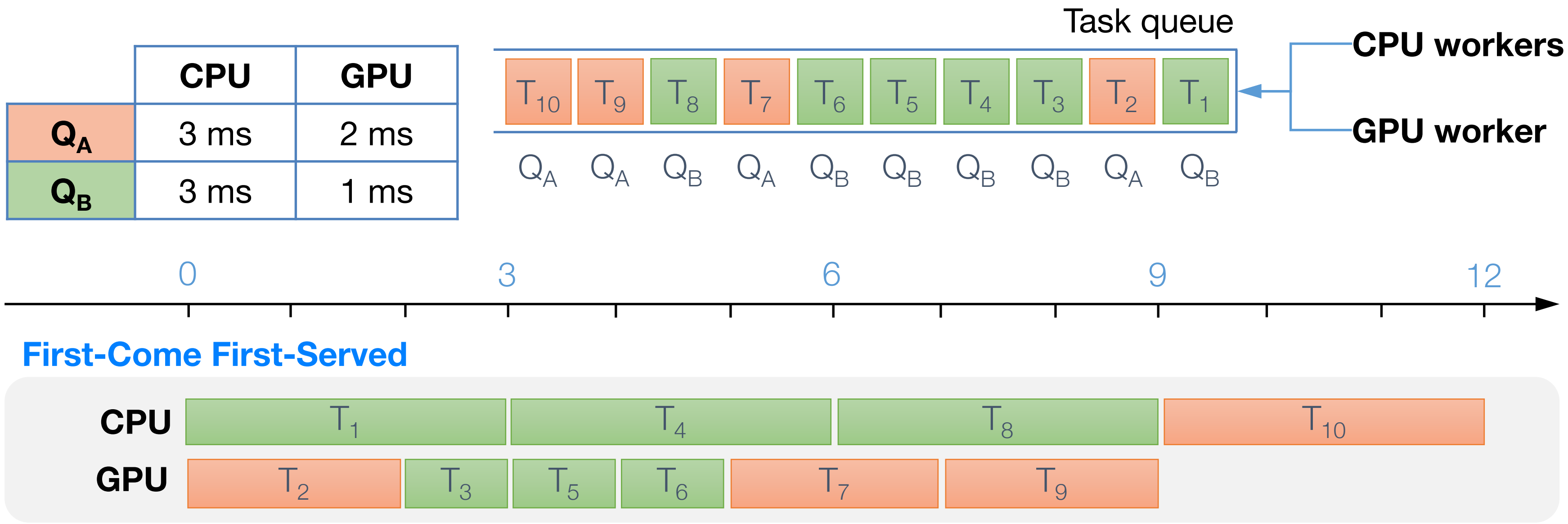
☛ **Static scheduling under-utilises processors**

First-Come First-Serve Task Scheduling?

Assign tasks to processors first-come, first-serve

– CPU/GPU execute both Q_A and Q_B tasks

	CPU	GPU
Q_A	3 ms	2 ms
Q_B	3 ms	1 ms



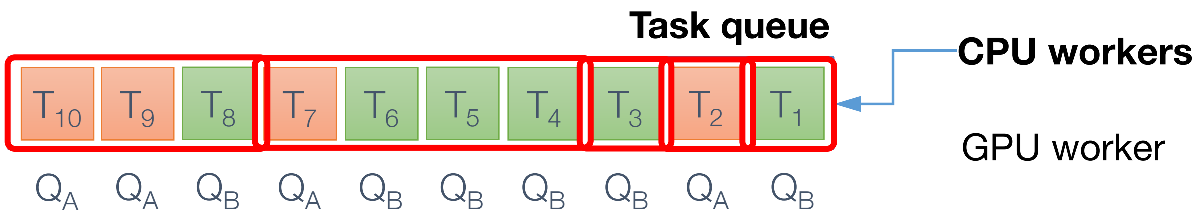
☛ FCFS ignores effectiveness of processors for given task

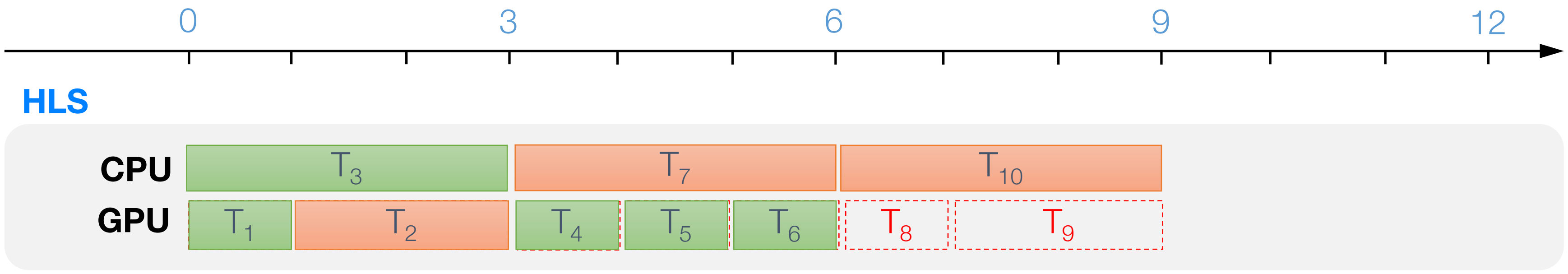
Heterogeneous Lookahead Scheduling (HLS)

Idea: Scheduler assigns tasks to **idle** processors **dynamically**

- **Skips** tasks that could be executed faster by another processor

	CPU	GPU
Q_A	3 ms	2 ms
Q_B	3 ms	1 ms



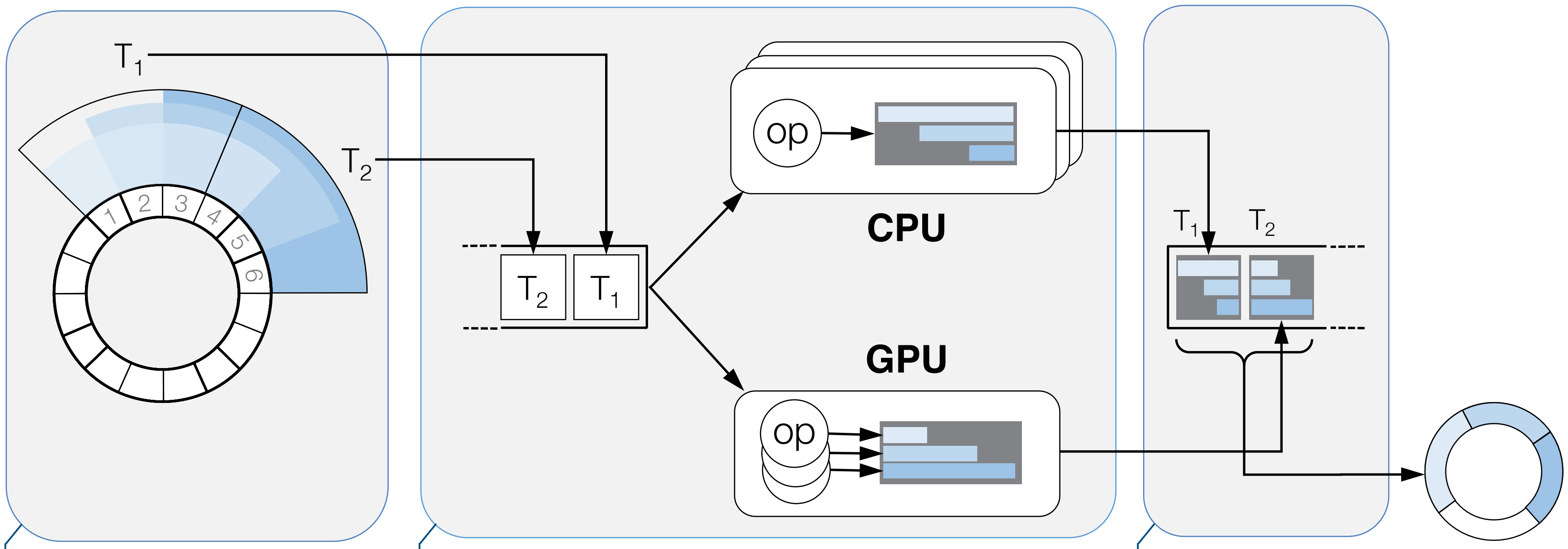


☛ HLS achieves aggregate throughput of all heterogeneous processors

SABER Hybrid Stream Processing Engine

Java
15K LOC

C & OpenCL
4K LOC



Dispatching stage
Dispatch fixed-size tasks

Scheduling & execution stage
Dequeue tasks based on HLS

Result stage
Merge & forward partial window results

Roadmap

SABER: Hybrid stream processing engine for heterogeneous servers

[SIGMOD'16]

(1) How to **parallelise computation** on modern hardware?

☛ Avoid coupling **system parameters** with **processing semantics**

(2) How to utilise **heterogeneous servers**?

☛ **Hybrid execution** utilises all heterogeneous processors

(3) Experimental **performance results**

Experimental Evaluation

PCIe 3.0 x16

10 Gbps
NIC

Intel Xeon
2.6 GHz

16 cores **64 GB RAM**

Ubuntu Linux 14.04

NVIDIA Quadro
K5200

2,304 cores **8 GB RAM**

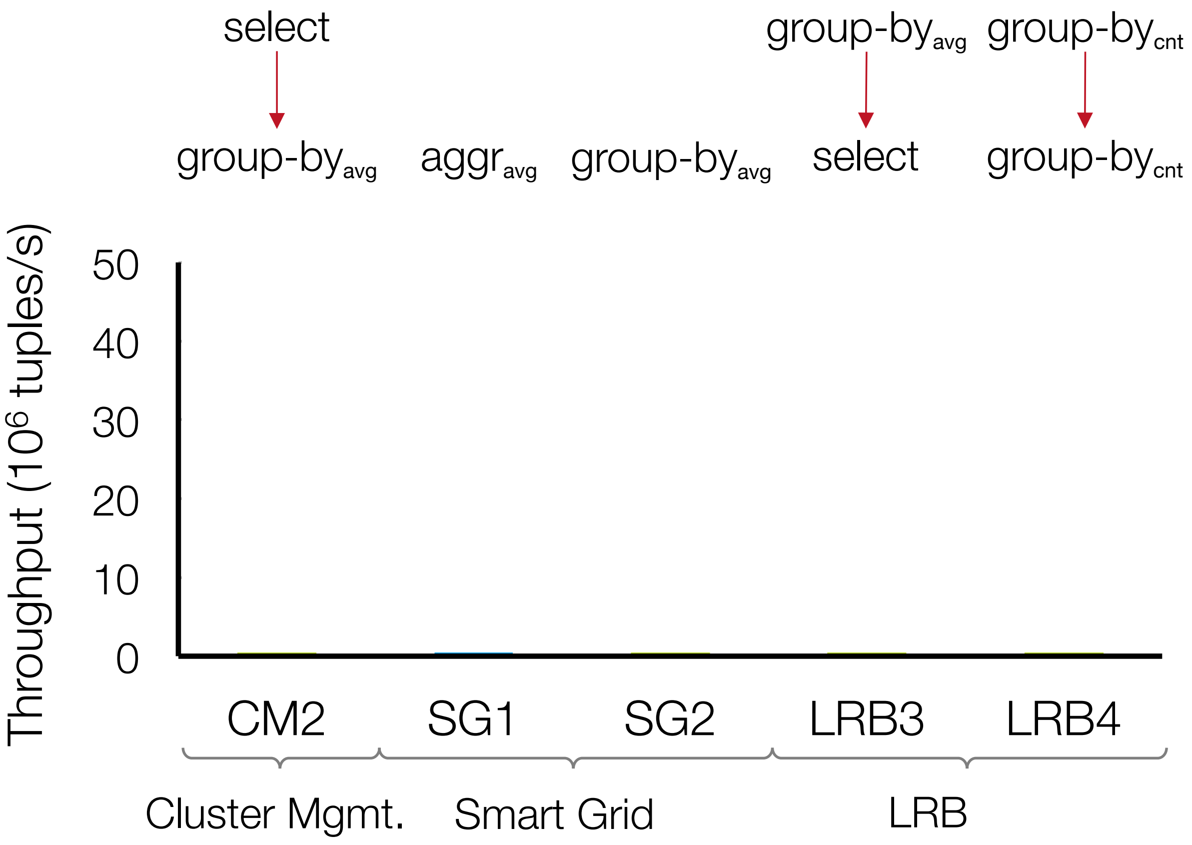
NVIDIA driver 346.47

Google Cluster Data
144M jobs events from Google infrastructure

SmartGrid Measurements
974M plug measurements from houses

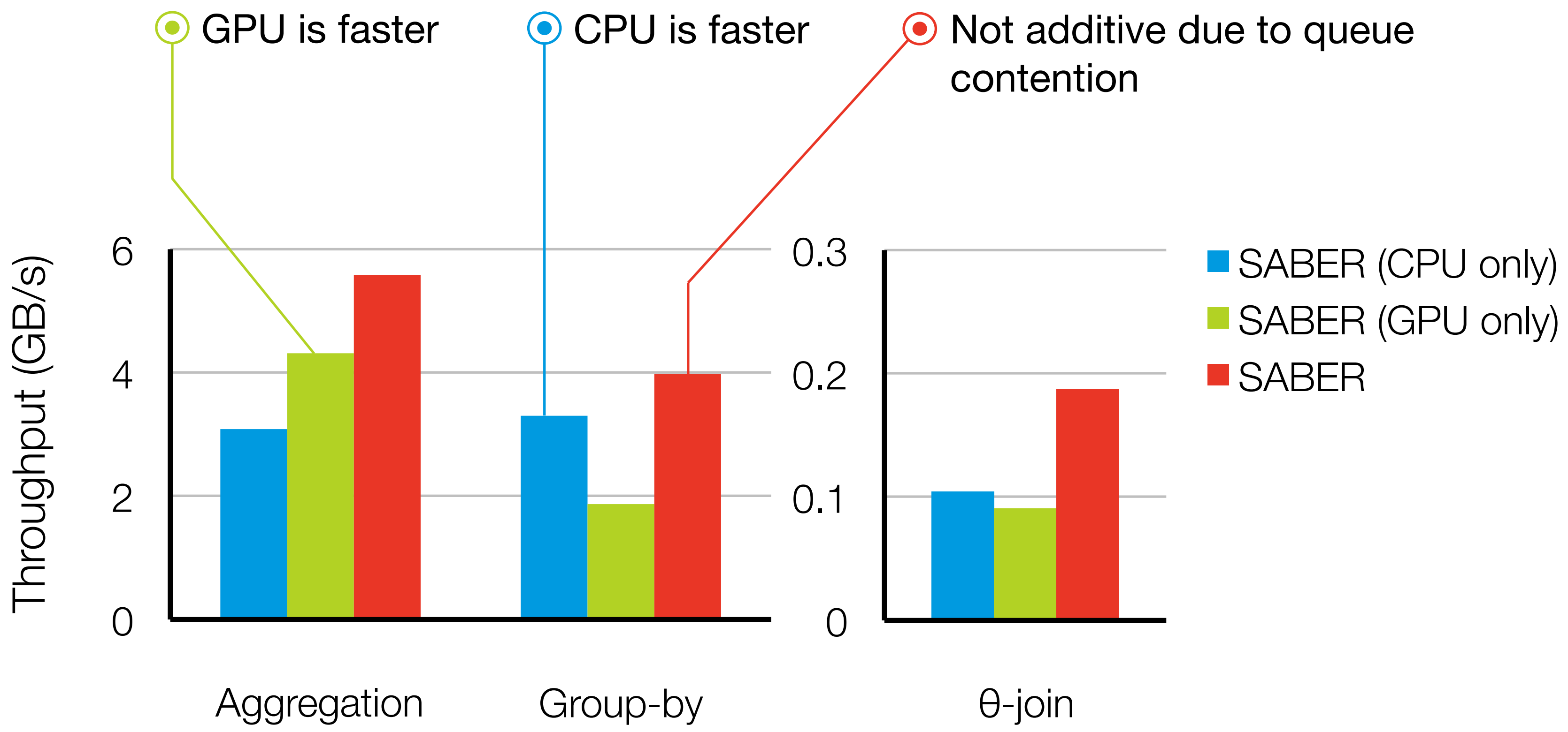
Linear Road Benchmark
11M car positions and speed on highway

What is SABER's Performance?



☛ SABER exploits both **CPUs** and **GPUs effectively** for different queries

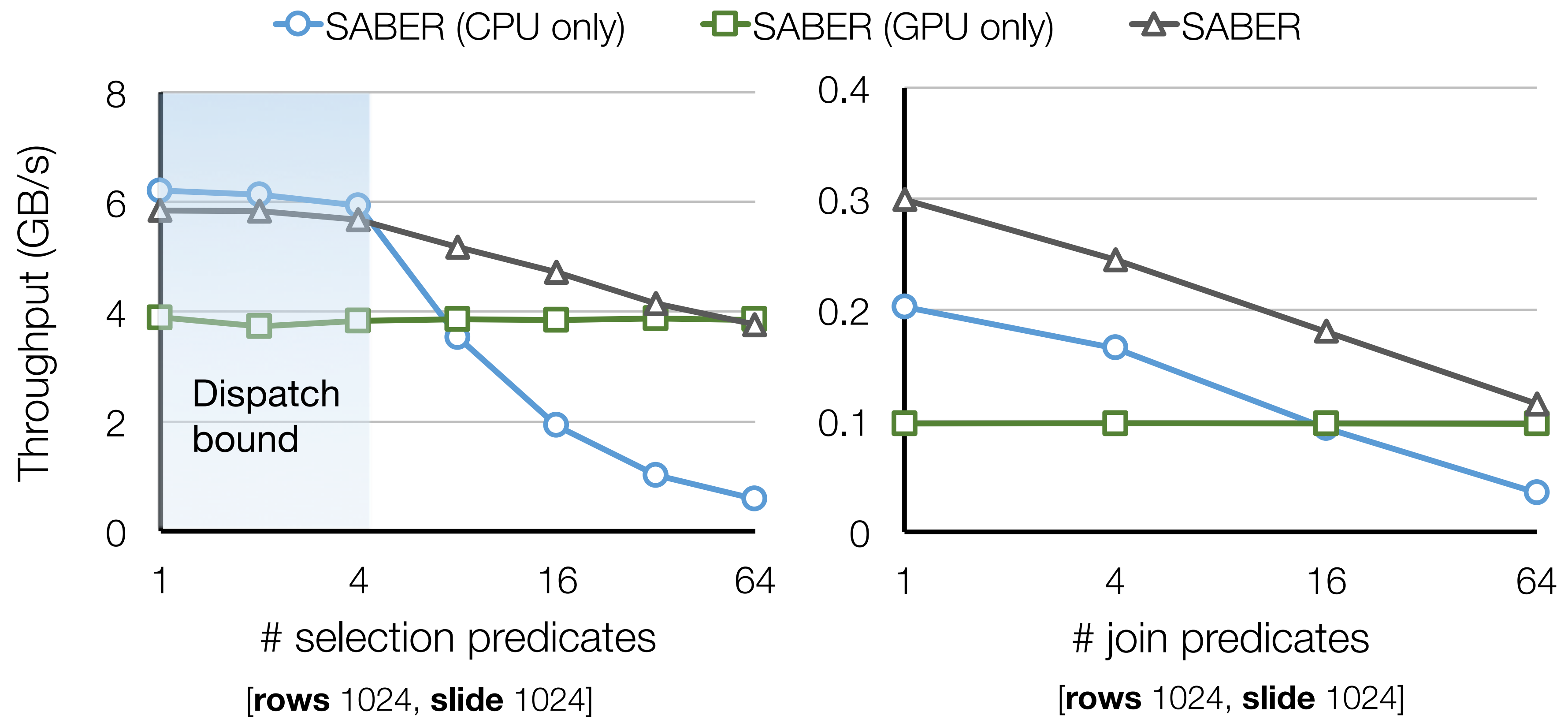
Is Hybrid Throughput Additive?



☛ **Aggregate throughput** of CPU + GPU always **highest**

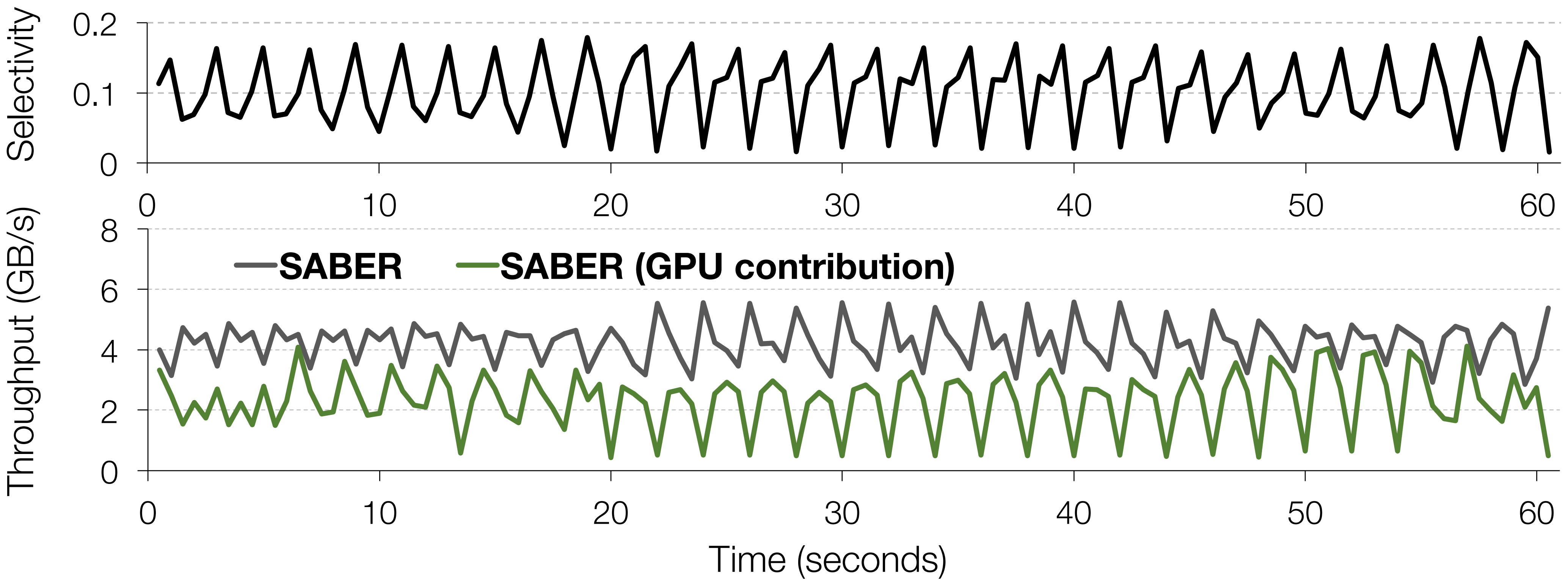
What is the Trade-Off between CPUs and GPUs?

Hybrid processing model benefits from GPU's ability to process complex predicates fast



Does SABER Adapt to Workload Changes?

HLS periodically uses idle, non-preferred processor to run tasks to update query task throughput matrix



☛ **Higher selectivity → more predicates evaluated → GPU preferred**

Summary

Heterogeneous servers have huge impact on **data-intensive systems**

- Shift from **scale out** to **scale up** model
- Need new **general-purpose system designs** for heterogeneous servers

SABER: Hybrid Stream Processing Engine for CPUs & GPUs

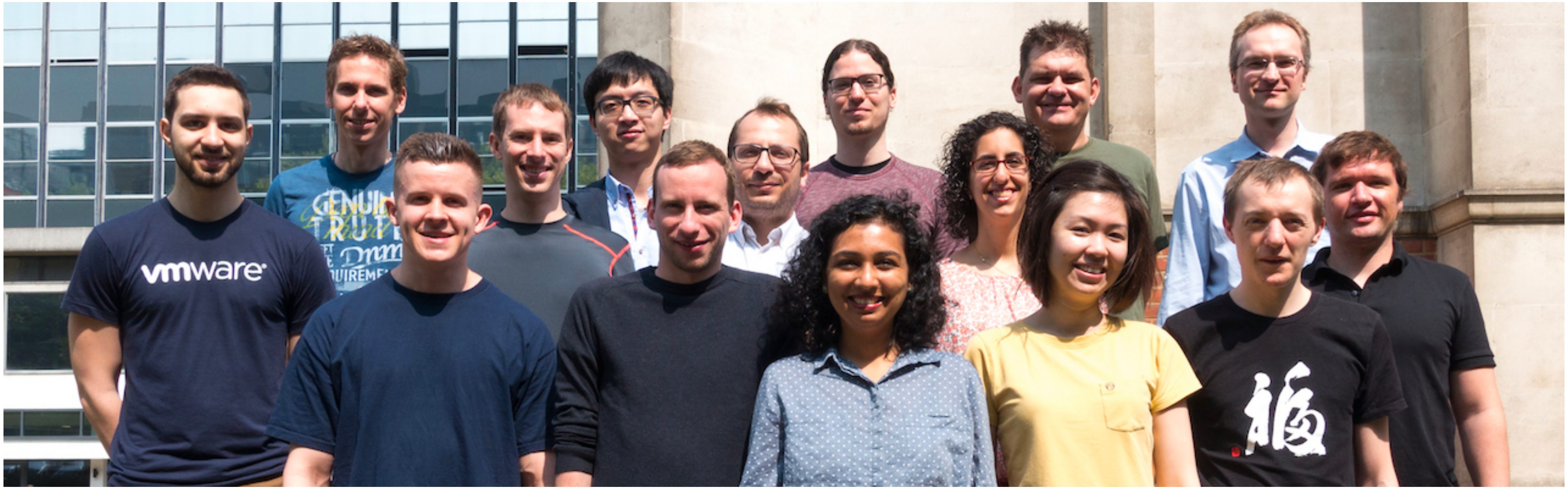
(1) Parallelise computation to fit hardware capabilities

☛ **Decouple hardware/system parameters** from **processing semantics**

(2) Fully utilise all heterogeneous processors independently of workload

☛ **Hybrid processing model** to achieve aggregate CPU/GPU throughput

Acknowledgement:
LSDS Group at Imperial College London



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Post-docs, PhDs

Thank you!
Any Questions?

Peter Pietzuch
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