RDFS Reasoning on Massively Parallel Hardware

Norman Heino, Jeff Z. Pan

University of Leipzig,
Germany
AKSW Research Group

University of Aberdeen,
United Kingdom
Dept. of Computing Science

RDFS reasoning

- Interpreting RDFS vocabulary can give rise to new triples
- Model-theoretic semantic conditions from RDF semantics document
- Incomplete set of rules
    - we use subset with exactly two antecedents

(5)	*p* rdfs:subPropertyOf *q*	& *q* rdfs:subPropertyOf *r*	⟹ *p* rdfs:subPropertyOf *r*
(11)	*C* rdfs:subClassOf *D*	& *D* rdfs:subClassOf *E*	⟹ *C* rdfs:subClassOf *E*
(2)	*s p o*	& *p* rdfs:domain *D*	⟹ *s* rdf:type *D*
(3)	*s p o*	& *p* rdfs:range *R*	⟹ *o* rdf:type *R*
(7)	*s p o*	& *p* rdfs:subPropertyOf *q*	⟹ *s q o*
(9)	*s* rdf:type *B*	& *B* rdfs:subClassOf *C*	⟹ *s* rdf:type *C*

RDFS reasoning

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Preliminaries

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- No rules with ‚trivial‘ entailments

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- No rules with ‚trivial‘ entailments
- Ignore non-authorative statements
- Results obtained w/o axiomatic triples

Special cases

(7)-1	s langProp_1 o	&	langProp_1 `rdfs:subPropertyOf` langProp_2	$\Longrightarrow$	s langProp_2 o
(7)-2	s langProp o	&	langProp `rdfs:subPropertyOf` q	$\Longrightarrow$	$s\ q\ o$
(7)-3	$s\ p\ o$	&	p `rdfs:subPropertyOf` langProp	$\Longrightarrow$	s langProp o
(7)-4	$s\ q\ o$	&	p `rdfs:subPropertyOf` q	$\Longrightarrow$	$s\ q\ o$

Special cases

~~(7)-1~~	~~s langProp$_1$ o~~	~~&~~	~~langProp$_1$ `rdfs:subPropertyOf` langProp$_2$~~	~~$\Longrightarrow$~~	~~s langProp$_2$ o~~
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(7)-4	$s\ q\ o$	&	p `rdfs:subPropertyOf` q	$\Longrightarrow$	$s\ q\ o$

Parallel RDFS reasoning

Parallel RDFS reasoning

- Cluster-based approaches
  - MapReduce – Urbani et al. (2009)
  - DHT – Kaoudi et al. (2008)
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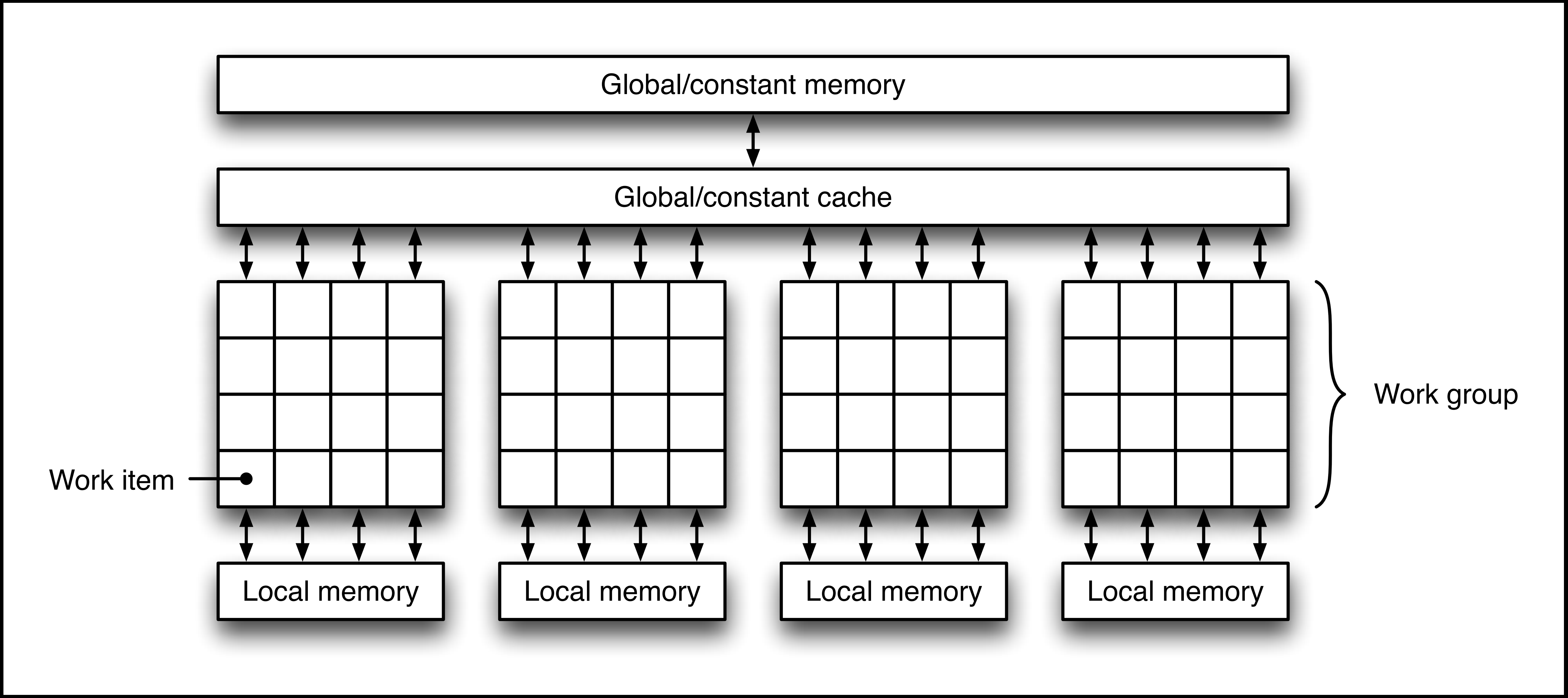
Our platform: single host, massively parallel commodity hardware with shared memory

Challenge: develop algorithm that allows for fine-grained parallelism

OpenCL

- Vendor-agnostic model and API for heterogenous parallel computation
- Khronos standard
- *GPU*, CPU, accellerators (Cell, DSPs)
- Host program controls submission of compute kernels and data to hardware
- Compute kernels written in C99 subset

OpenCL memory model



Big picture

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1. Parsing

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    - one `std::vector` per column
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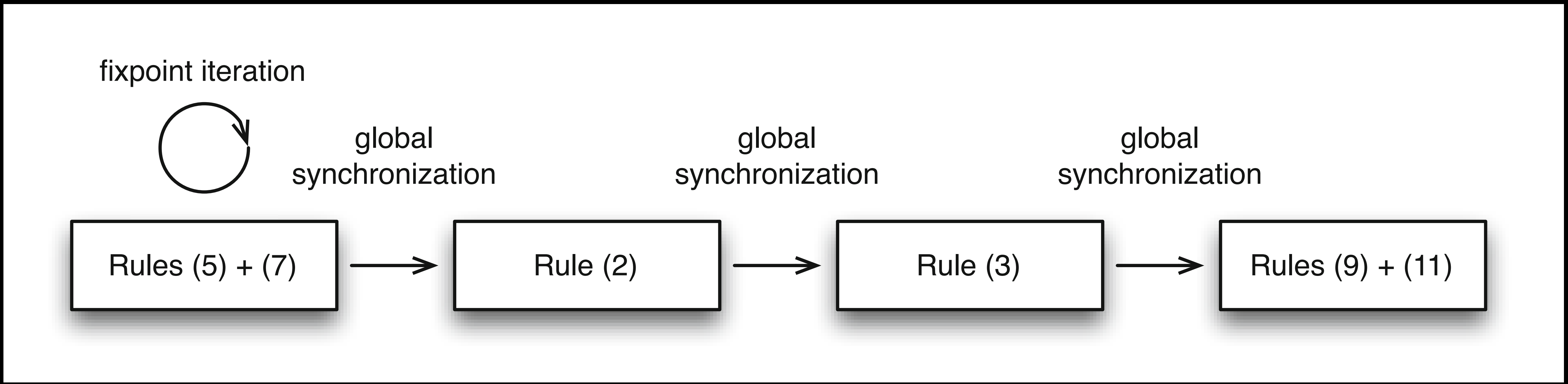
2. Dictionary encoding
3. In-memory storage
   - one `std::vector` per column
   - indexed by *hash*(triple)
4. Copying data to device (PCIe bus)
5. Rule application on device
6. Copying back, storing results

Rule implementation



- Could produce schema triples
- Independent of (2), could be run in parallel

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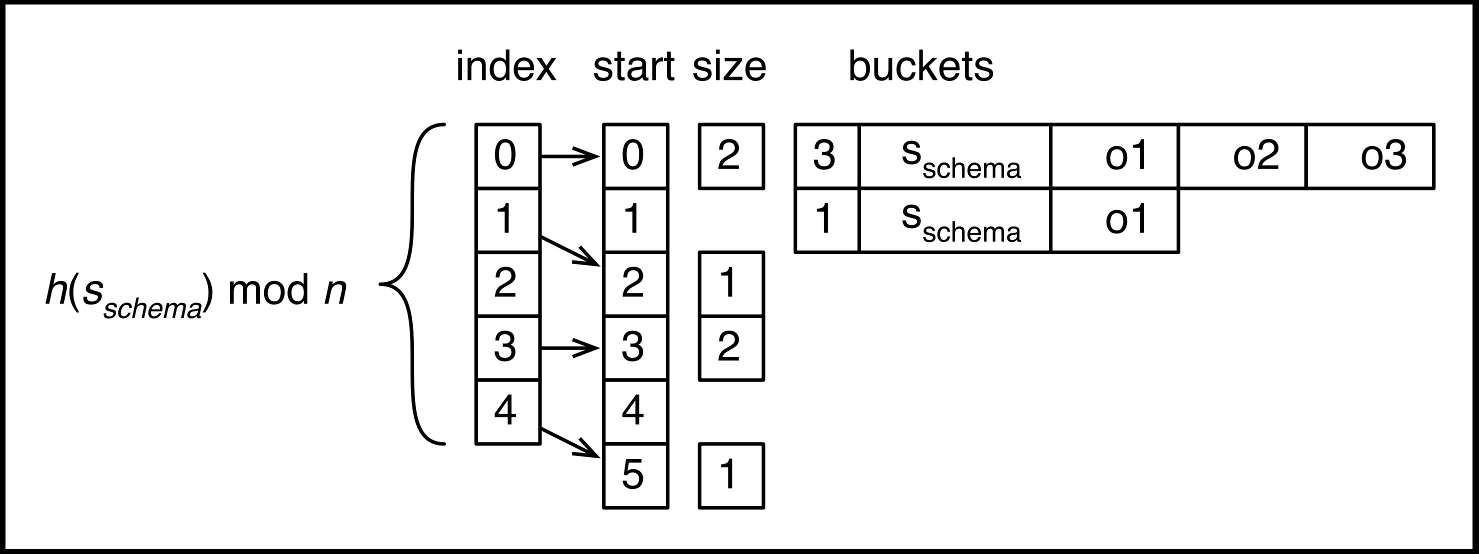
TC-based rules

- Transitive property hierachies have a sparse adjacency matrix
  - Quadratic algorithm (Warshall) is infeasible
- Host-run serial implementation based on work by Nuutila

Join rules

- Join instance triple with schema subject
  - counting results
  - computing index
- Materialize result triples in two passes



The duplicate problem

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Duplicates by rule

	DBpedia			YAGO2 Core		
Rule	Triples	Duplicates	Ratio	Triples	Duplicates	Ratio
(5)	0	0	–	0	19	>
(7)	0	0	–	3,551,361	88,477	0.03
(2)	368,832	7,630,029	21	6,450,781	13,453,038	2.1
(3)	568,715	4,939,870	8.7	409,193	1,511,512	3.7
(11)	259	610	2	3,398,943	366,764	0.1
(9)	0	8,329,278	>	6,685,946	3,173,957	0.5
(11+9)	259	10,398,328	42,162	35,061,599	57,969,000	1.7
all	1,650,607	23,775,152	14	45,766,218	89,370,361	2.0

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Global duplicate prevention

- Hash table in global device memory
- Each thread materializes triple only if not in hash table
- Table is static (not updated)

Local deduplication

1. Sort triples in local memory
2. Count adjacent duplicates
3. Caclulate new duplicate-free index
4. Zero out duplicates, rearrange unique values

Local dedup example

data vector

index vectors

Local dedup example

data vector

2	1	5	3	5	4	1	4

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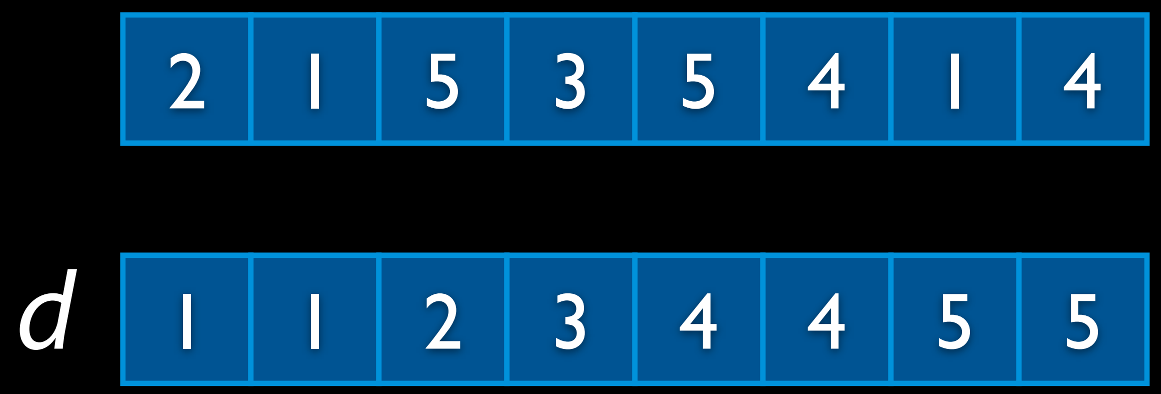


Local dedup example

data vector

2	1	5	3	5	4	1	4

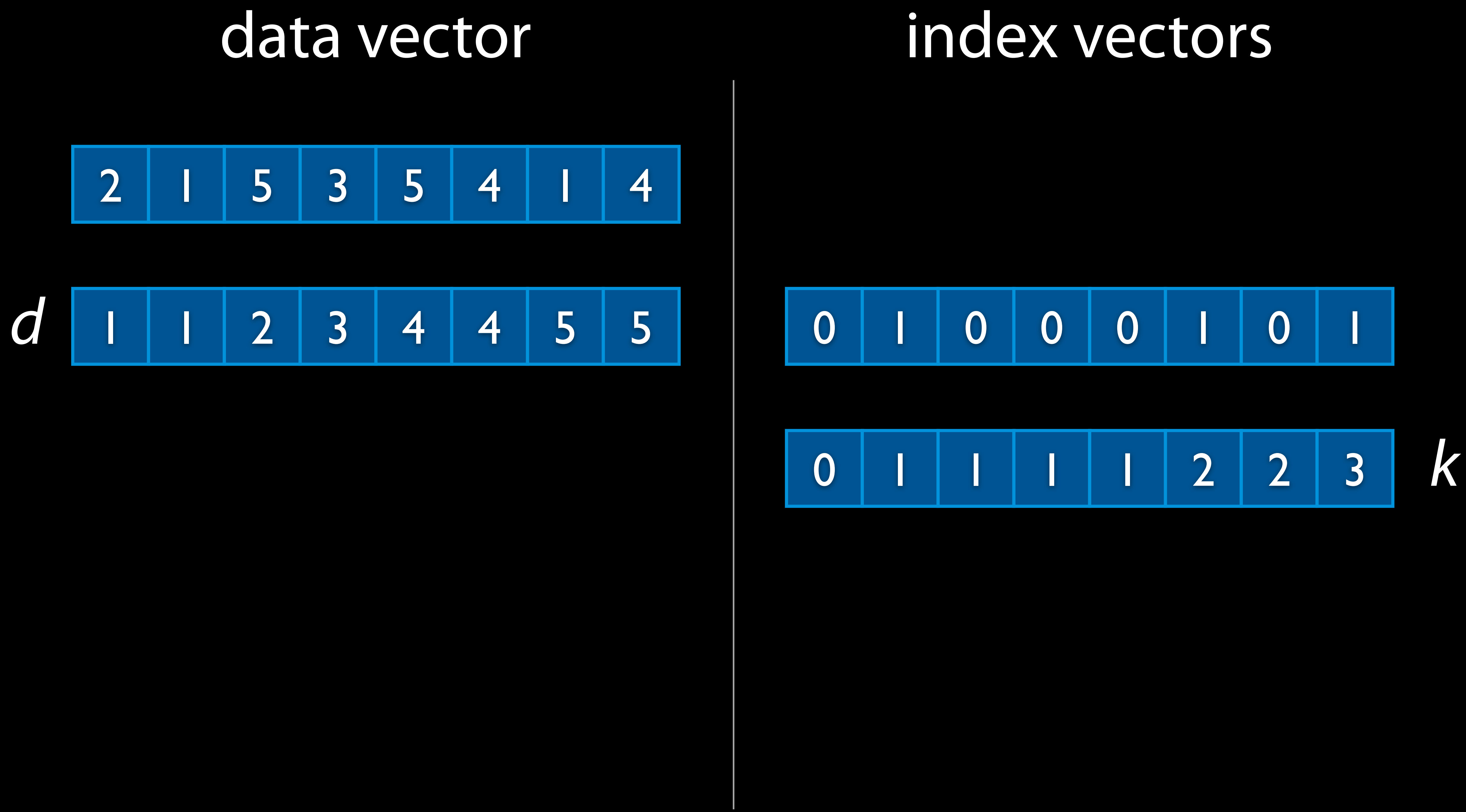
d

1	1	2	3	4	4	5	5

index vectors

0	1	0	0	0	1	0	1

Local dedup example



Local dedup example

data vector

	2	1	5	3	5	4	1	4
d	1	1	2	3	4	4	5	5

index vectors

0	1	0	0	0	1	0	1	
0	1	1	1	1	2	2	3	k

$$r_i = \begin{cases} d_{i+k_i} & i + k_i < |d| \\ 0 & \text{else} \end{cases}$$

Local dedup example

data vector

2	1	5	3	5	4	1	4

d

1	1	2	3	4	4	5	5

r

1	2	3	4	5	0	0	0

$$r_i = \begin{cases} d_{i+k_i} & i + k_i < |d| \\ 0 & \text{else} \end{cases}$$

index vectors

0	1	0	0	0	1	0	1

k

0	1	1	1	1	2	2	3

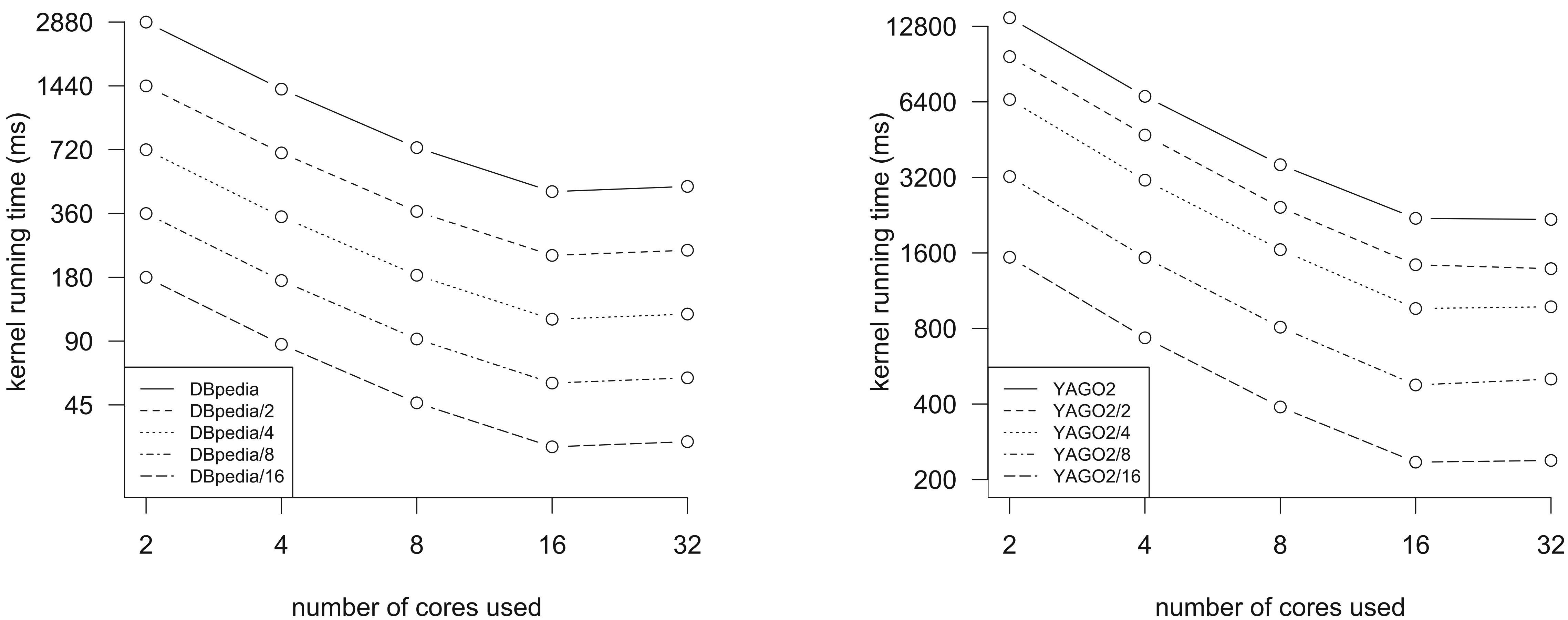
Experiments

- Exp1: study scalability on different levels of hardware parallelism
  - performed on 4 CPU server with 32 CUs
- Exp2: study efficacy of duplicate removal strategies
  - performed on 20 CU GPU device
- Exp3: compare to previous work

Datasets

- DBedia ontology, infobox types, infobox triples:
  - ~26M triples
  - ~1.7M new closure triples
- YAGO2Core
  - ~36M triples
  - ~46M new closure triples
- Both scaled to 1/2, …, 1/16th of instance triples plus all schema triples

Results – Exp1



(a) DBpedia (b) YAGO2 Core

Results – Exp2

Dataset	Strategy	Kernel time (ms)	Closure time (ms)	Duplicates	Speedup
DBpedia	None	28.444	6,884.15	23,775,152	
	L	120.915	6,083.76	12,165,520	13.2 %
	G	52.305	6,635.60	1,511,758	3.7 %
	L+G	117.400	6,557.94	1,057,470	5 %
YAGO2/8	None	25.565	21,625.19	31,552,221	
	L	187.169	19,554.09	2,399,898	10.6 %
	G	53.948	21,622.31	29,357,936	0 %
	L+G	215.947	19,807.66	1,786,753	9.2 %

Results – Exp3

	Input triples	Output triples	Damásio (ms)	Our system (ms)	Speedup
T2	366,490	3,617,532	23,619.90	9,038.89	2.6 $\times$
T6	1,942,887	4,947,407	18,602.43	1,964.49	9.5 $\times$

- T6 also performed on M/R cluster in > 3 min

CPU – GPU comparison

Device	Kernel execution (ms)	Total (ms)
Core i7 3770 (CPU)	647.311	5509.92
Radeon HD 7870 (GPU)	114.683	5881.54

Conclusions/future work

- RDFS reasoning is can be done *massively* parallel
- Shared memory can be used for efficient parallel duplicate reduction
- low ALU:fetch ratio is unvaforable for GPU devices

- Data compression
- Multiple devices
- Reasoning on the FPU
- Complete implementation w.r.t. RDF semantics

Complexity of RDFS reasoning

- RDFS reasoning is in *P,* if *G* does not contain blank nodes (ter Horst, 2002)
- RDFS reasoning is *P*-complete (i.e. in *P* but not in *NC; Patel-Schneider, 2012)*
- NC – problem can be solved in $O(\log^c n)$ time using $O(n^k)$ processors
    - i.e. you can trade parallelism for complexity