Lazy Data-Oriented Evaluation Strategies

3rd ACM SIGPLAN Workshop on Functional High-Performance Computing

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The talk is about using laziness to make *parallel programs run faster*.

Intro and Motivation

- What we want to achieve:
  - higher performance through more flexible parallelism control
- How:
  - through the use of lazy evaluation and circular programming techniques
  - develop a number of advanced parallelism control mechanisms
  - embed them into evaluation strategies
- Performance results:
  - comparative study of performance using a constructed test program and a Barnes-Hut algorithm

Glasgow parallel Haskell (GpH)

- support for semi-explicit parallelism through GpH extension
- GpH Primitives
  - *par* to specify parallelism

    ```
    x `par` y => y
    ```

    x is *sparked* to be potentially evaluated in parallel.
  - *pseq* to enforce sequential ordering

    ```
    x `pseq` y => y
    ```

    x is evaluated to WHNF.
  - purely functional, stateless code

- Evaluation Strategies
  - build on top of basic primitives
  - raise the level of abstraction even higher
  - separate coordination from computation aspects

```
data Eval a = Done a

runEval::Eval a->a
runEval (Done x) = x

type Strategy a = a->Eval a

rseq, rpar::Strategy a
rseq x = x `pseq` Done x
rpar x = x `par` Done x

using::a->Strategy a->a
x `using` strat = runEval (strat x)
```

GpH Primitives and Evaluation Strategies
Examples

sequential factorial

```
-- factorial example
fact m n
  | m == n = m
  | otherwise =
                (left * right)
      where
        mid   = (m + n) `div` 2
        left  = fact m mid
        right = fact (mid + 1) n
```

GpH Primitives and Evaluation Strategies
Examples

introducing parallelism using primitives

```
-- factorial example
fact m n
  | m == n = m
  | otherwise = left `par` right `pseq`
                (left * right)
      where
        mid   = (m + n) `div` 2
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GpH Primitives and Evaluation Strategies
Examples

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GpH Primitives and Evaluation Strategies

Examples

using evaluation strategies

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  | m == n = m
  | otherwise =
                (left * right)
      where
        mid   = (m + n) `div` 2
        left  = fact m mid
        right = fact (mid + 1) n
        strategy result = do
           rpar left
           rseq right
           return result
```

define strategy separate from algorithm

GpH Primitives and Evaluation Strategies

Examples

using evaluation strategies

```
-- factorial example
fact m n
  | m == n = m
  | otherwise =
                (left * right) `using` strategy
      where
        mid   = (m + n) `div` 2
        left  = fact m mid
        right = fact (mid + 1) n
        strategy result = do
           rpar left
           rseq right
           return result
```

apply strategy with `using`

GpH Primitives and Evaluation Strategies (2)

Examples

Primitives

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-- factorial example
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  | m == n = m
  | otherwise = left `par` right `pseq`
                (left * right)
      where
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Evaluation Strategies

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– clear separation of coordination from computation code

– more structured parallel program

GpH Primitives and Evaluation Strategies (2)

Examples

Primitives

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– clear separation of coordination from computation code

– more structured parallel program

Data parallel strategies

```
-- e.g. parallel map
parMap strat f xs =
  map f xs `using` parList strat
  -- where strat specifies the eval degree
```

GpH Primitives and Evaluation Strategies (2)

Examples

Primitives

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-- factorial example
fact m n
  | m == n = m
  | otherwise = left `par` right `pseq`
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Evaluation Strategies

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  | otherwise = (left * right)
                `using` strategy
      where
        mid   = (m + n) `div` 2
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        strategy result = do
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– clear separation of coordination from computation code

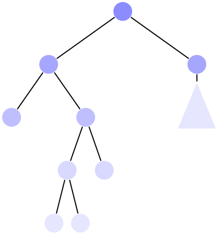
– more structured parallel program

Data parallel strategies

```
-- e.g. parallel map
parMap strat f xs =
  map f xs `using` parList strat
  -- where strat specifies the eval degree
```

```
-- chunking to control granularity
parMapChunk strat f xs =
  map f xs `using` parListChunk size strat
```

Tree Strategies

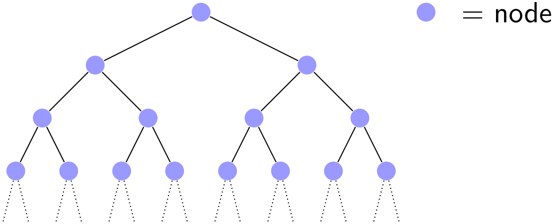


Tree Strategies

- 2 classes of strategies
  1. Basic Strategies
     - more general
     - use no/traditional parallelism control mechanisms
     - e.g. `parTree`, `parTreeDepth`
  2. Advanced Strategies
     - use advanced mechanisms
       - flexible
       - use laziness inherently
       - fuel-based control
     - e.g. `parTreeLazySize`, `parTreeFuelXXX`

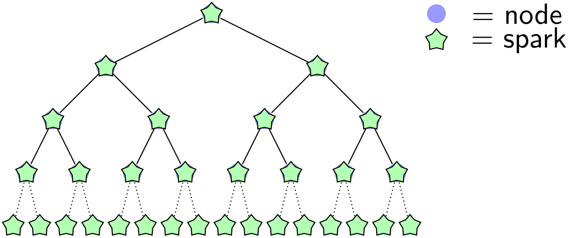
Basic Strategies

Naive with no parallelism control



Basic Strategies

Naive with no parallelism control

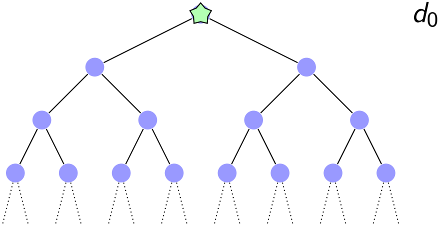


- parTree
  - analogous to parList
  - uncontrolled spark creation – high overhead!
  - basic implementation of traverse from Traversable typeclass

Traditional Parallelism Control Mechanisms

Depth-thresholding with `parTreeDepth`

Info flow	down
Context	path length
Parameter	d



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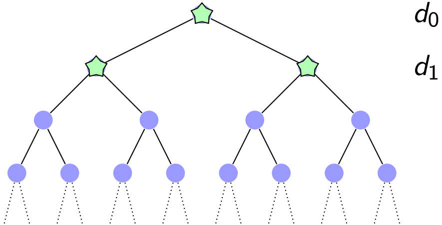

Traditional Parallelism Control Mechanisms

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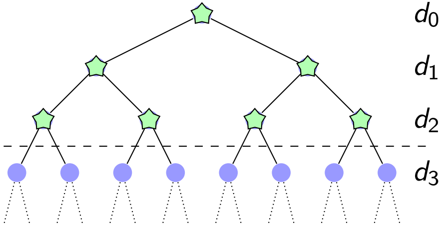

Traditional Parallelism Control Mechanisms

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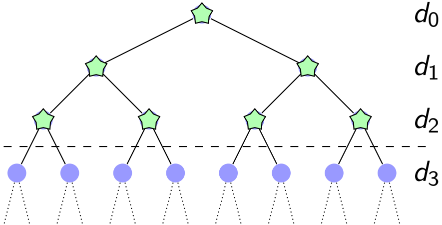
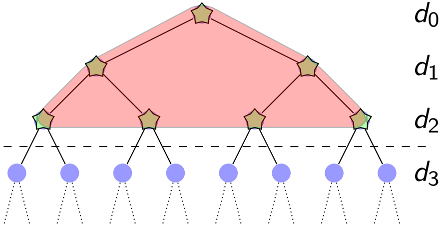


- Summary:
  - simple, low overhead and predictable parallelism
  - works pretty well for regular tree

Traditional Parallelism Control Mechanisms

Depth-thresholding with `parTreeDepth`

Info flow	down
Context	path length
Parameter	*d*

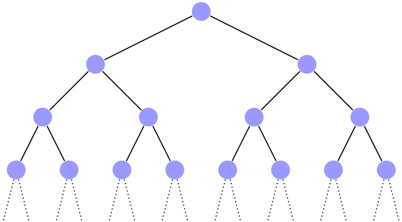


- Summary:
  - simple, low overhead and predictable parallelism
  - works pretty well for regular tree
  - lacks flexibility for unbalanced trees – parallelism may not reside in the top *d* level

Traditional Parallelism Control Mechanisms

Synthesised size info as threshold

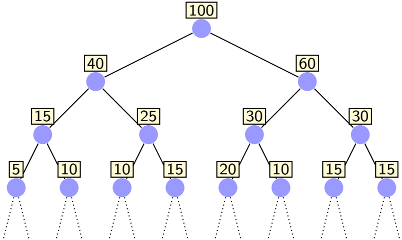
Info flow	up
Context	global
Parameter	*s*



Traditional Parallelism Control Mechanisms

Synthesised size info as threshold

Info flow	up
Context	global
Parameter	*s*

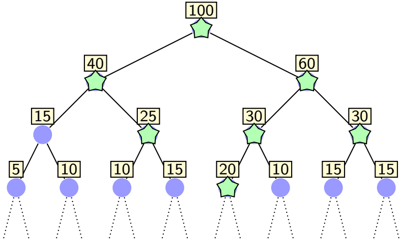


- size synthesised in a single annotation pass

Traditional Parallelism Control Mechanisms

Synthesised size info as threshold

Info flow	up
Context	global
Parameter	s

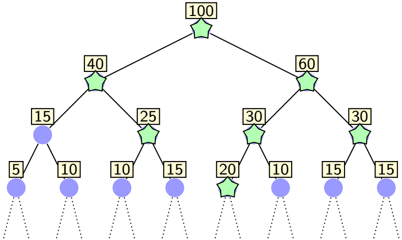


- size synthesised in a single annotation pass
- ensures sparks are not created for smaller sub-trees e.g. $s < 20$

Traditional Parallelism Control Mechanisms

Synthesised size info as threshold

Info flow	up
Context	global
Parameter	s

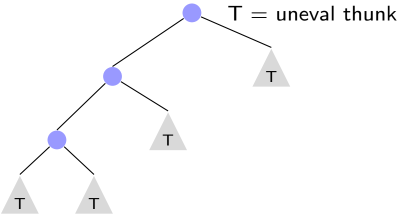


- size synthesised in a single annotation pass
- ensures sparks are not created for smaller sub-trees e.g. $s < 20$
- carries administrative overhead

Advanced Mechanisms

Lazy size computation

Info flow	down
Context	local
Parameter	s



- removes the need for initial annotation traversal
- lazily checks size of subnodes evaluating only up to what is needed
- size check function is implemented using (algebraic) natural instead of (atomic) integer type

```
-- returns tree when it has established that the sub-tree
       contains at least s nodes without a full
      deconstruction.
isBoundedSize s t = lazy_check t > s

lazy_check::QTree tl tn -> Natural
lazy_check = ...
```

Advanced Mechanisms

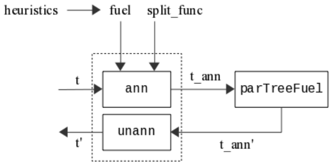
Fuel-based control

- fuel
  - limited resources distributed among nodes
  - similar to “potential” in amortised cost
  - and the concept of “engines” to control computation in Scheme
- parallelism generation (sparks) created until fuel runs out
- more flexible to throttle parallelism

Advanced Mechanisms

Fuel-based control

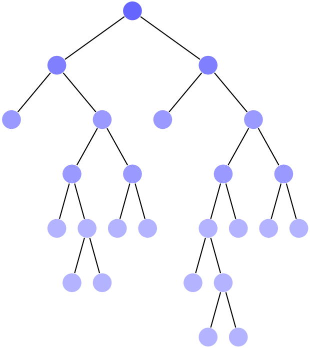
- fuel split function
    - flexibility of defining custom function specifying how fuel is distributed among sub-nodes
    - e.g. *pure*, *lookahead*, *perfectsplit*
    - split function influences which path in the tree will benefit most of parallel evaluation



annotate tree with fuel info based on `split_func`

Fuel-based Control Mechanism

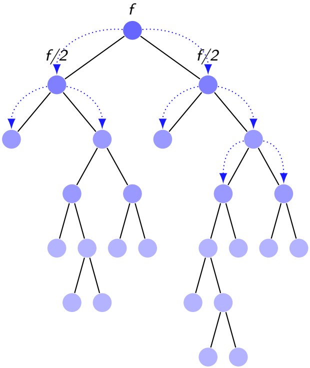
pure, lookahead, perfectsplit



Fuel-based Control Mechanism

pure, lookahead, perfectsplit

pure	
Info flow	down
Context	local
Parameter	*f*

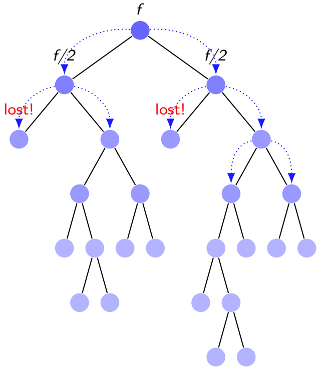


- Characteristics of pure version
  - splits fuel equally among sub-nodes

Fuel-based Control Mechanism

pure, lookahead, perfectsplit

pure	
Info flow	down
Context	local
Parameter	*f*



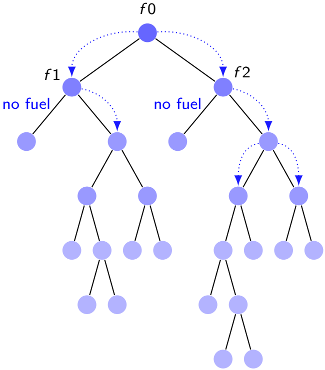
- Characteristics of pure version
  - splits fuel equally among sub-nodes
  - fuel lost on outer nodes

Fuel-based Control Mechanism

pure, lookahead, perfectsplit

pure	
Info flow	down
Context	local
Parameter	f

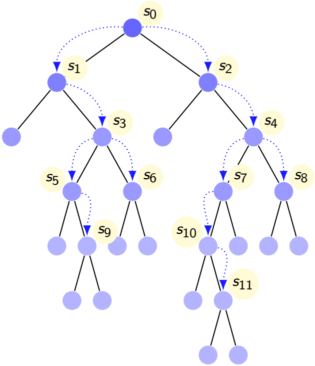
lookahead	
Info flow	down/limited
Context	local (N)
Parameter	f



- Characteristics of lookahead version
  - looks ahead N level down before distributing unneeded fuel
  - more efficient distribution

Fuel-based Control Mechanism

pure, lookahead, perfectsplit



pure

Info flow	down
Context	local
Parameter	f

lookahead

Info flow	down/limited
Context	local (N)
Parameter	f

perfectsplit

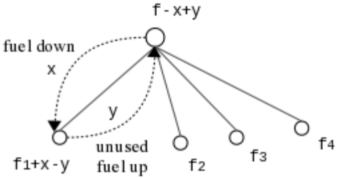
Info flow	down
Context	global
Parameter	f

- Characteristics of perfectsplit version
  - perfect fuel splitting
  - distributes fuel based on sub-node sizes

Advanced Mechanisms

Fuel-based control

- bi-directional fuel transfer – *giveback* version
  - fuel is passed down from root
  - fuel is given back if tree is empty or fuel is unused
  - *giveback* mechanism is implemented via circularity

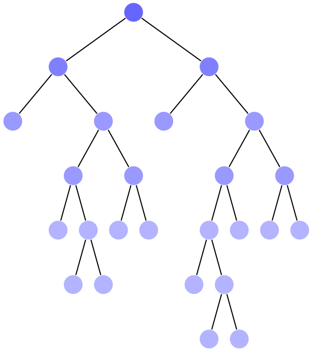


- fuel represented using list of values instead of an (atomic) integer
- giveback mechanism is effective in enabling additional parallelism for irregular tree
  - distribution carries deeper inside the tree

Fuel-based Control Mechanism

giveback fuel flow

giveback	
Info flow	down/up
Context	local
Parameter	*f*



Fuel-based Control Mechanism

giveback fuel flow

giveback	
Info flow	down/up
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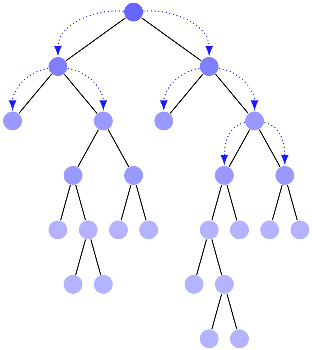


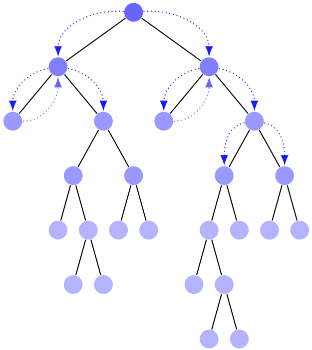
- f_in: fuel down

Fuel-based Control Mechanism

giveback fuel flow

giveback

Info flow	down/up
Context	local
Parameter	f



- f_in: fuel down
- f_out: fuel up

Fuel-based Control Mechanism

giveback fuel flow

giveback	
Info flow	down/up
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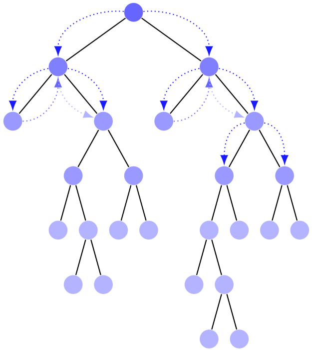

- f_in: fuel down
- f_out: fuel up
- f_in': fuel reallocated

Advanced Mechanisms

Fuel-based control with giveback using circularity

```
-- | Fuel with giveback annotation
annFuel_giveback::Fuel -> QTree tl -> AnnQTree Fuel tl
annFuel_giveback f t = fst \$ ann (fuelL f) t
 where
  ann::FuelL -> QTree tl -> (AnnQTree Fuel tl,FuelL)
  ann f_in E                = (E,f_in)
  ann f_in (L x)            = (L x,f_in)
  ann f_in (N (Q a b c d)) = (N (AQ (A (length f_in)) a' b' c' d'),
      emptyFuelL)
   where
    (f1_in:f2_in:f3_in:f4_in:_) = fuelsplit numnodes f_in
    (a',f1_out) = ann (f1_in ++ f4_out) a
    (b',f2_out) = ann (f2_in ++ f1_out) b
    (c',f3_out) = ann (f3_in ++ f2_out) c
    (d',f4_out) = ann (f4_in ++ f3_out) d
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Advanced Mechanisms

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Advanced Mechanisms

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```

- fuel flows back in a circular way

Tree Strategies

Summary

Strategy	Type	Info flow	Context	Parameter	Heuristics
parTree	element-wise sparks	-	-	-	-
parTreeDepth	depth threshold	down	path length	d	yes
parTreeSizeAnn	annotation-based	up	global	-	-
parTreeLazySize	lazy size check	down	local	s	yes
parTreeFuelAnn	annotation-based			f	yes
- pure	equal fuel distr	down	local		
- lookahead	check next n nodes	down/limited	N	N	
- giveback	circular fuel distr	up/down	local		
- perfectsplit	perfect fuel distr	down	global		

Performance Evaluation

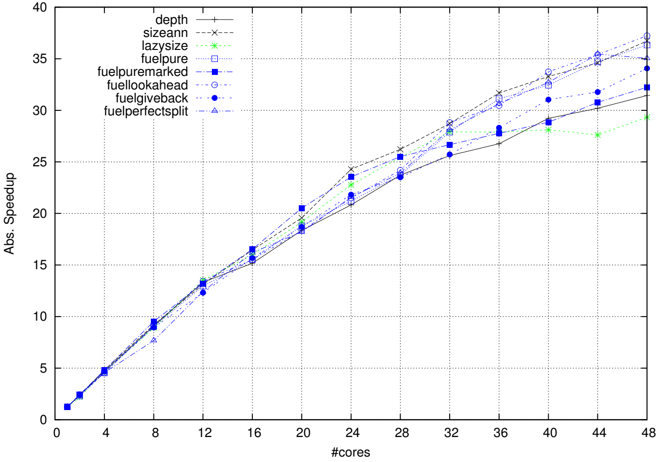
Setup

- Machine
  - 48-core *server-class many-core* (1.4Ghz)
  - 8 NUMA regions (remote region access is 2.2x local access)
  - 64GB RAM
  - running Linux
- Compiler: `ghc-7.6.1`
- Libraries:
  - `parallel-3.2`
  - `pardata-0.1` extended set of advanced strategies for tree-like data structures (includes heuristics for auto-tuning)
- Applications: test program, Barnes-Hut, sparse matrix multiplication, (LSS)

Performance Evaluation (1)

– normal depth distr.
– homo/hetero comp.

Test program speedups on 1-48 cores. 100k elements.

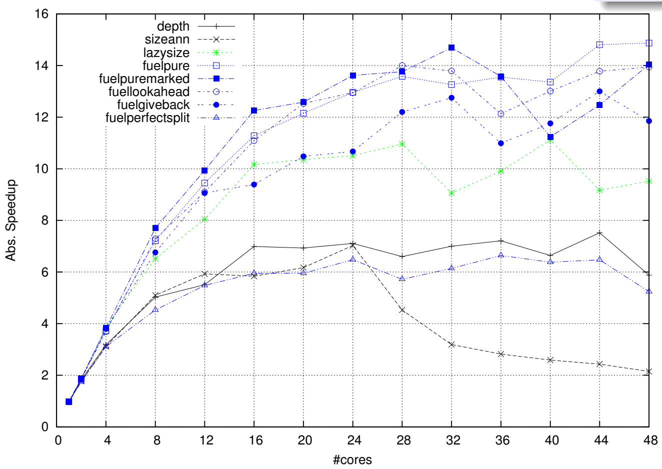


- performance: improvement of $> 18\%$ (depth vs. best fuel)
- giveback hitrate e.g. for $f = 100$, number of hits=478

Performance Evaluation (2)

Barnes-Hut speedups on 1-48 cores. 2 million bodies. 1 iteration.

– multiple clusters distr.
– parallel force comp.
– no restructuring of seq code necessary



- pure fuel gives best perf. – simple but cheap fuel distr.; lookahead/giveback within 6/20%
- fuel ann/unann overheads: 11/4% for 2m bodies
- more instances of giveback due to highly irregular input (7682 for 100k bodies, $f = 2000$)

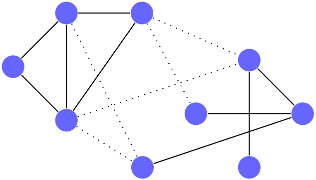
Summary

- we use laziness to improve parallel performance
- we use laziness and circular programs in the coordination code to achieve additional flexibility
- we develop a number of flexible parallelism control mechanisms in the form of evaluation strategies
- we demonstrate improved performance on a constructed program and 2 non-trivial applications, in particular, with irregular trees

Ongoing Work

Graph Strategies

- develop similar evaluation strategies for graphs



- depth-first and breadth-first traversal strategies on graphs
- apply techniques (e.g. thresholding, fuel) to graph strategies
- algorithms: shortest path, max clique
- SICSA Multicore Challenge III[1]

[1] http://www.macs.hw.ac.uk/sicsawiki/index.php/Challenge_PhaseIII

Paper and sources

- Full paper, sources for strategies and test programs:
  `http://www.macs.hw.ac.uk/~dsg/gph/papers/abstracts/fhpc14.html`
- Email: {pt114, h.w.loidl}@hw.ac.uk

Thank you!