Parallel Programming and Heterogeneous Computing

E1 - Outlook: Problem Classes

Max Plauth, *Sven Köhler*, Felix Eberhardt, Lukas Wenzel, and Andreas Polze
Operating Systems and Middleware Group

Hasso Plattner Institut
Digital Engineering · Universität Potsdam

A View from Berkeley

The Landscape of Parallel Computing Research: A View from Berkeley

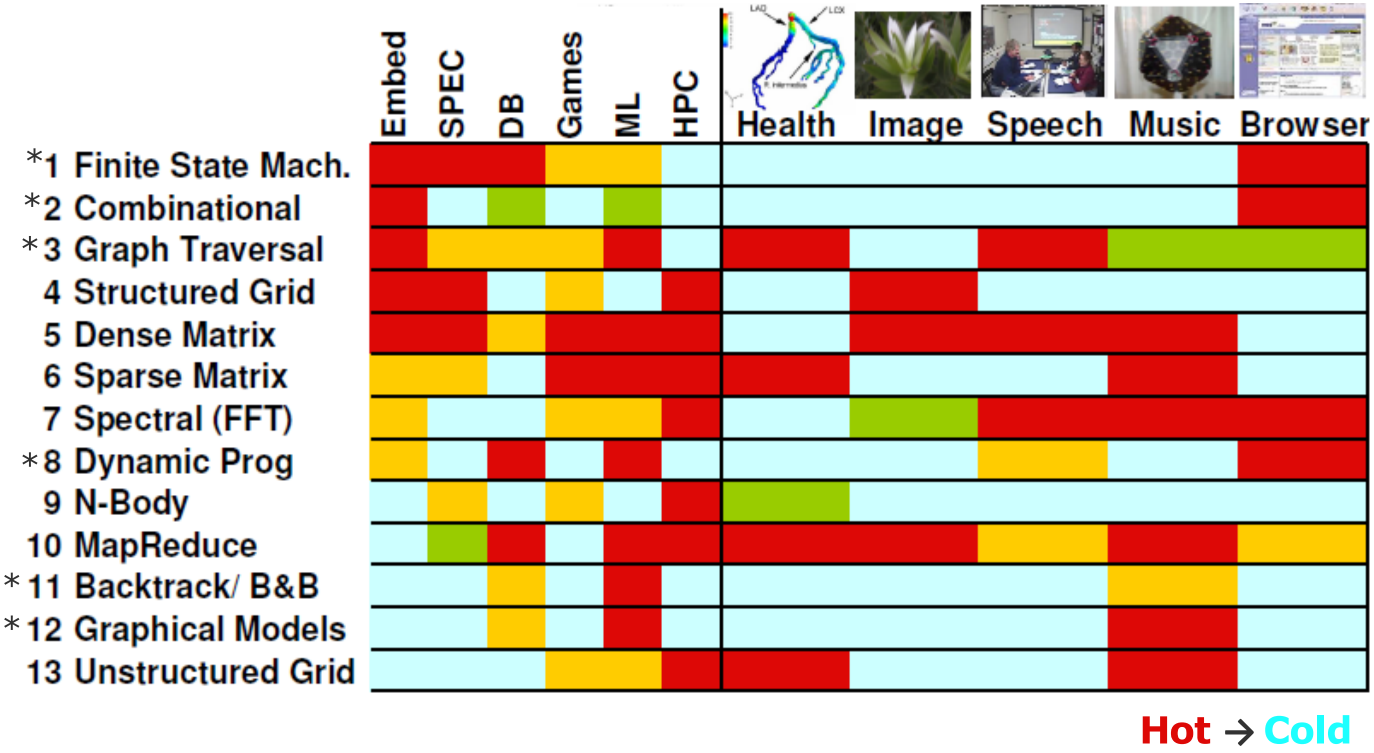
Krste Asanovic
Ras Bodik
Bryan Christopher Catanzaro
Joseph James Gebis
Parry Husbands
Kurt Keutzer
David A. Patterson
William Lester Plishker
John Shalf
Samuel Webb Williams
Katherine A. Yelick

1 Berkeley Dwarfs

A View From Berkeley

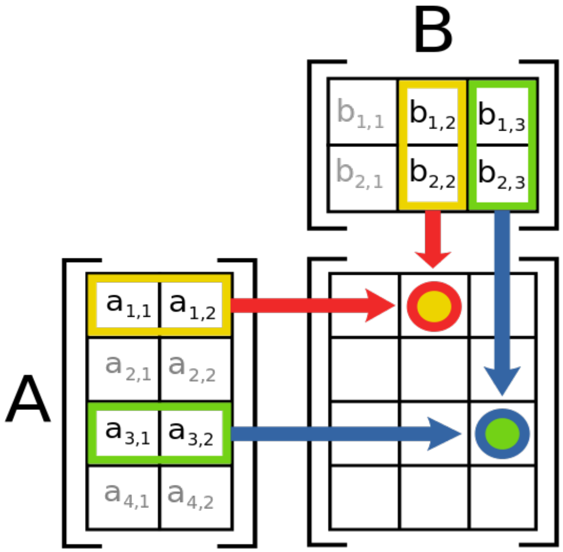
- Sources
  - EEMBC benchmarks (embedded systems), SPEC benchmarks
  - Database and text mining technology
  - Algorithms in computer design and graphics, machine learning
  - Original “7 Dwarfes” for supercomputing [Colella]
- “Anti-bechmarks”
  - Dwarfs are not tied to code or language artifacts
  - Can serve as understandable vocabulary across disciplines
  - Allow feasibility study of hardware and software design
    - No need to wait for applications being developed
- Relevance of single dwarfs widely differs
- One dwarf may be implemented based on an other one
- Reference implementations for different platforms exist

Dwarf Popularity
= How Compelling Apps Relate To Dwarfs



* added later

Dwarf 1: Dense Linear Algebra



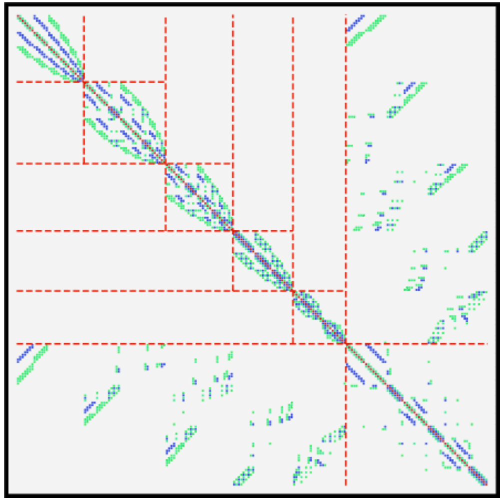
Classic vector and matrix operations

```
do i=1,n
  do j=1,n
    do k=1,n
      a(i,j) = a(i,j) + b(i,k)*c(k,j)
```

Frequent operation in computer graphics and as training step in machine learning

C = AxB

Dwarf 2: Sparse Linear Algebra

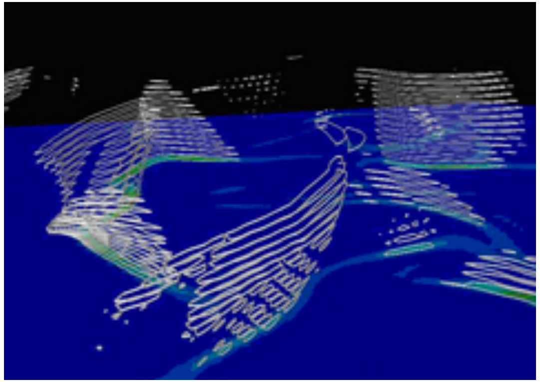


Operations on a sparse matrix (lots of zeros)

```
do i=1,n
  do j=row_start(i),row_start(i+1)-1
    y(i) = y(i) + val(j)*x(col_index(j))
```

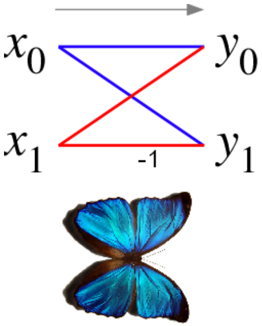
Complex data-dependency structure
Common in e.g. in graph problems.

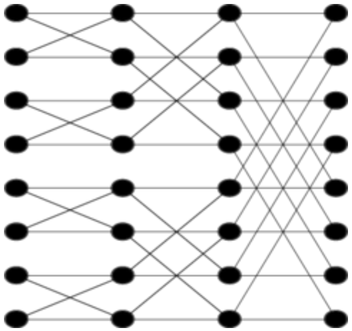
Dwarf 3: Spectral Methods



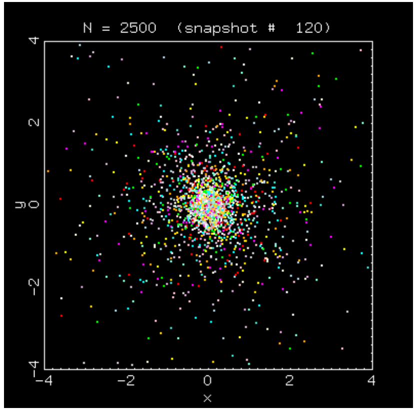
Data is converted into other domains, which means multiple stages with inter-depended data access patterns.

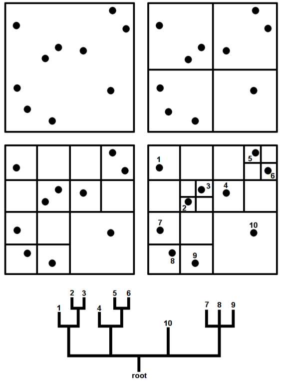
Common ML data preparation step, or used in signal processing.





Dwarf 4: N-Body Methods

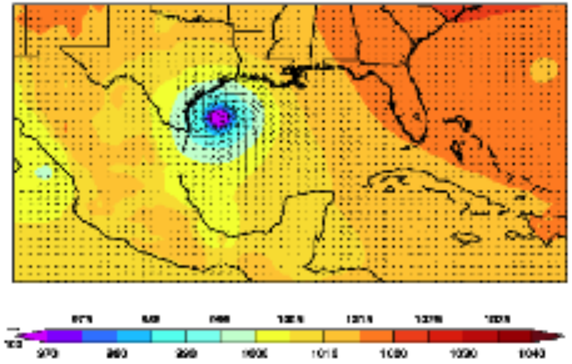


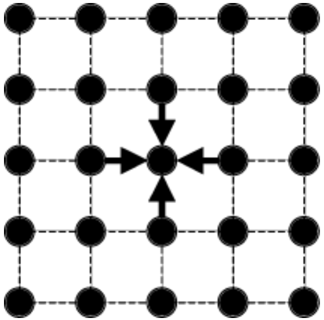


Calculations on interactions between
Many discrete points.

Large number of independent calculations
in a time step, followed by wide communication.

Dwarf 5: Structured Grid



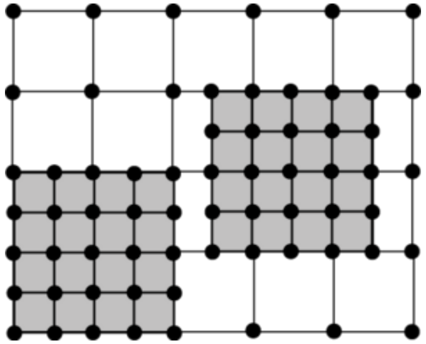


Data as a regular multidimensional grid: access is regular and statically determinable (strided).

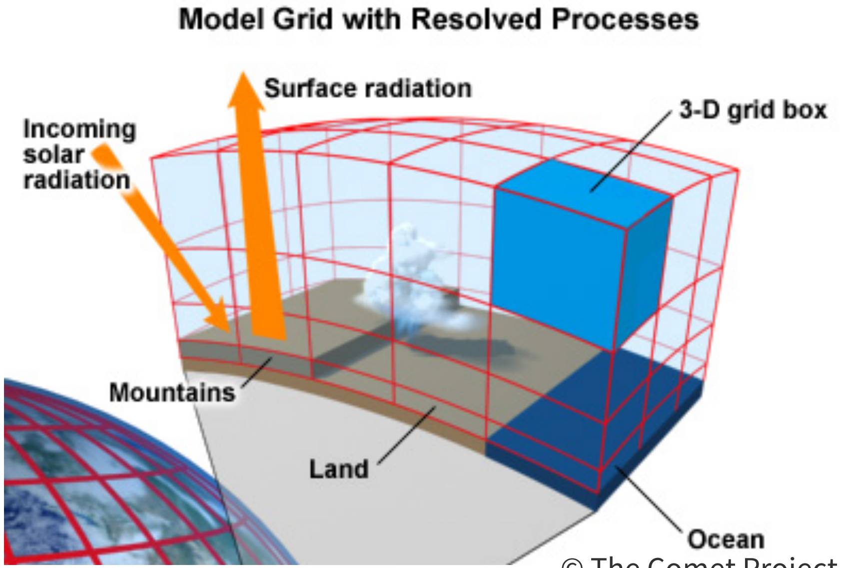
Computation is sequence of grid updates (all points are updated using values from a small neighborhood).

Typical Application: Weather simulations

Dwarf 5 Variant: Adaptive Mesh Refinement



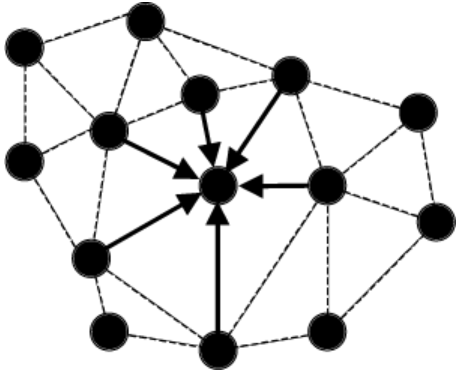
Overlaying higher-resolution grids across areas of interest. Requires complex indexing and difficult communication across nodes.

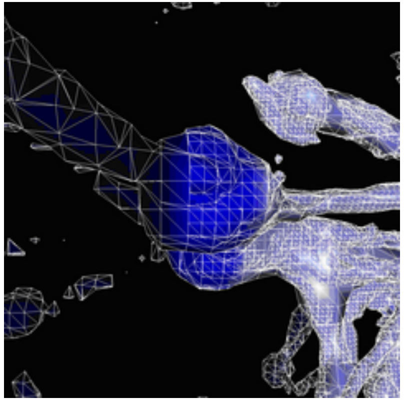


Example:

Modular Ocean Model

Dwarf 6: Unstructured Grid





Elements update neighbors in irregular mesh/grid with static or dynamic structure

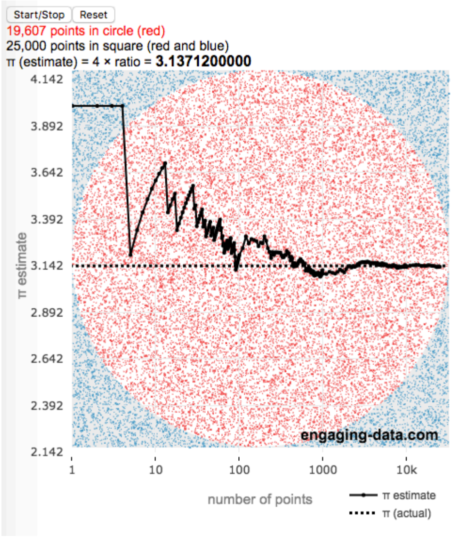
Problematic data distribution and access requirements, usually indirection by tables.

$$A'[B[C[i]]] = f(A[B[C[i+1]]] + A[B[C[i+2]]] + A[B[C[i+3]]])$$

Modelling domain (e.g. physics engine)

- Mesh represents surface or volume
- Entities are points, edges, faces, volumes, …
- Applying tension, temperature, pressure

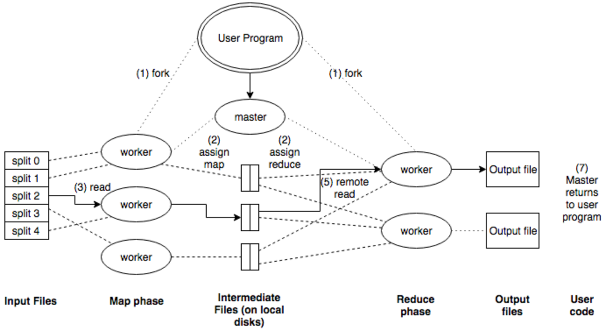
Dwarf 7: MapReduce (= "Monte Carlo")



Repeated independent execution of a function (e.g. RNG, map function), results aggregated.

Examples:

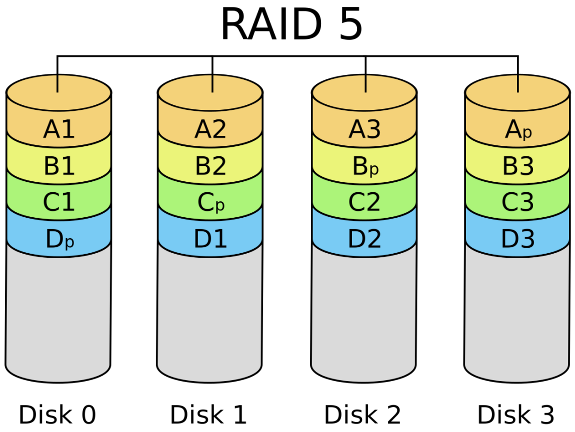
Monte Carlo Pi, BOINC (SETI@home), Optimization Protein Structure Prediction



Dwarf 8: Combinational Logic*

- AND, OR, XOR, …
- Exploit bit-level parallelism for high throughput
- Simple operations on very large amounts of variable-word-length data
- Parallel Mapping algorithms may be broken into data pipelines:
  - each processor executes part of the pipeline and then passes the data to the next processor
- Special-purpose hardware (or FPGAs)

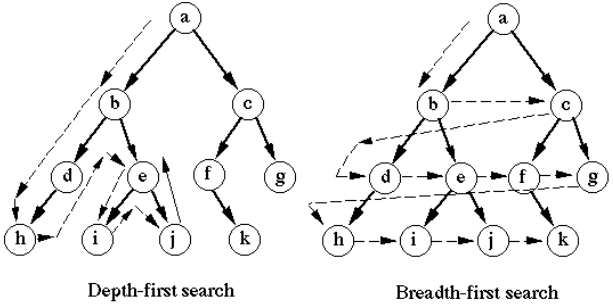
- Examples:
  - Networks and file systems: checksums, RAID
  - Data mining: population count, finding the number of `1`s in a word



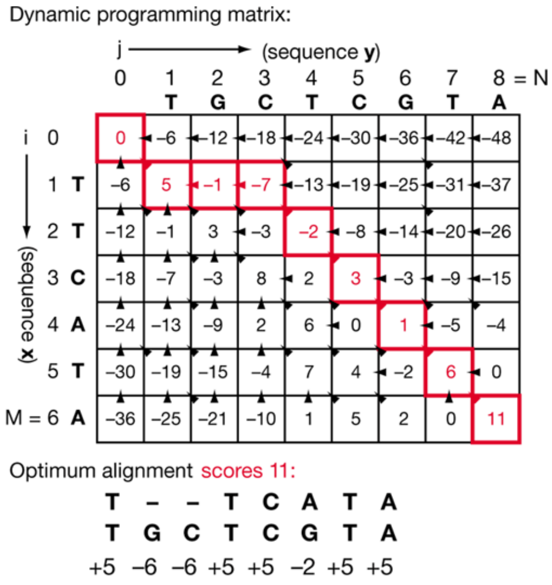
Dwarf 9: Graph Traversal*

- Traverse a number of objects and examine their characteristics **once**
- Usually indirect lookups and little computations
- Variation: searching
- Pointer chasing without much chance for more efficient processing

- Possible Optimizations (seldom feasible):
  - There may be locality in accesses to the graph (update graph storage)
  - There may be some processing per node that can reduce the effective cost of finding later nodes



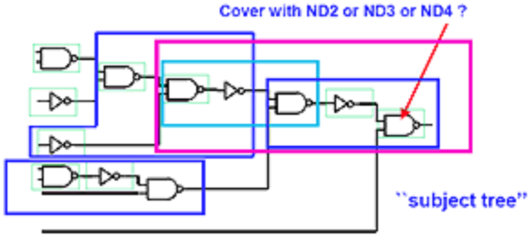
Dwarf 10(*): Dynamic Programming



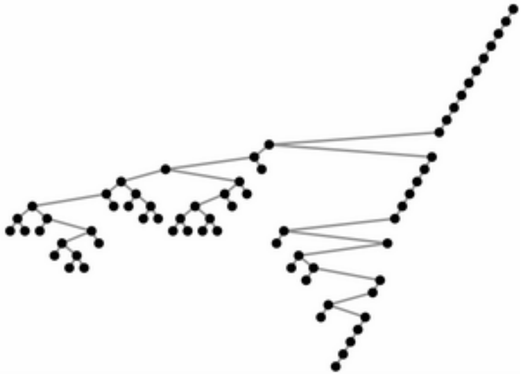
Compute optimal solutions by combining optimal, yet simpler overlapping subproblem solutions (typically use a table to avoid recomputation)

Examples:

circuit design, DNA sequence matching (Needleman–Wunsch), Viterbi, Knapsack, …

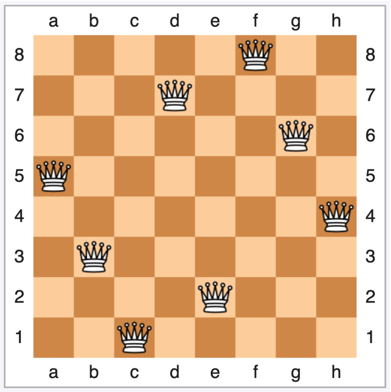


Dwarf 11(*): Branch-and-Bound



Global optimization problem in very large search space:

- Branches into subdivisions
- Rules out infeasible regions to optimize execution time and energy consumption

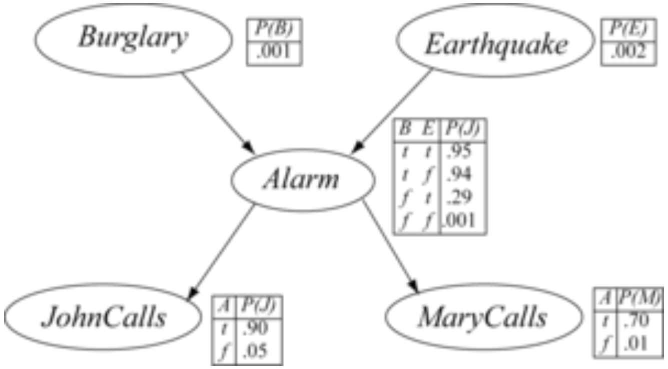


Examples:

Integer Linear Programming, Boolean Satisfiability, Combinatorial Optimization, Traveling Salesman, Constraint Programming, N-Queens

Dwarf 12(*): Graphical Models

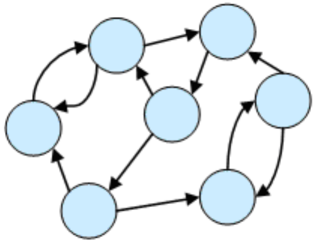
- A graph in which nodes represent variables, and edges represent conditional probabilities
- Bayesian networks, Hidden Markov models, neural networks
- Examples: AI, machine learning speech and image recognition
- Evaluation is a form of *Graph Traversal*, or *Dense-Linear Algebra*
- **Uniprocessor Mapping**:
  - Probabilistic aspect -> small amount of computation per node
  - Processing many observations and updating variables accordingly
- **Parallel Mapping**:
  - May be evaluated multiple times for a single problem
    -> Update conflicts possible
  - Simple: many graphical models can be evaluated for a single input



Dwarf 13(*): Finite State Machines

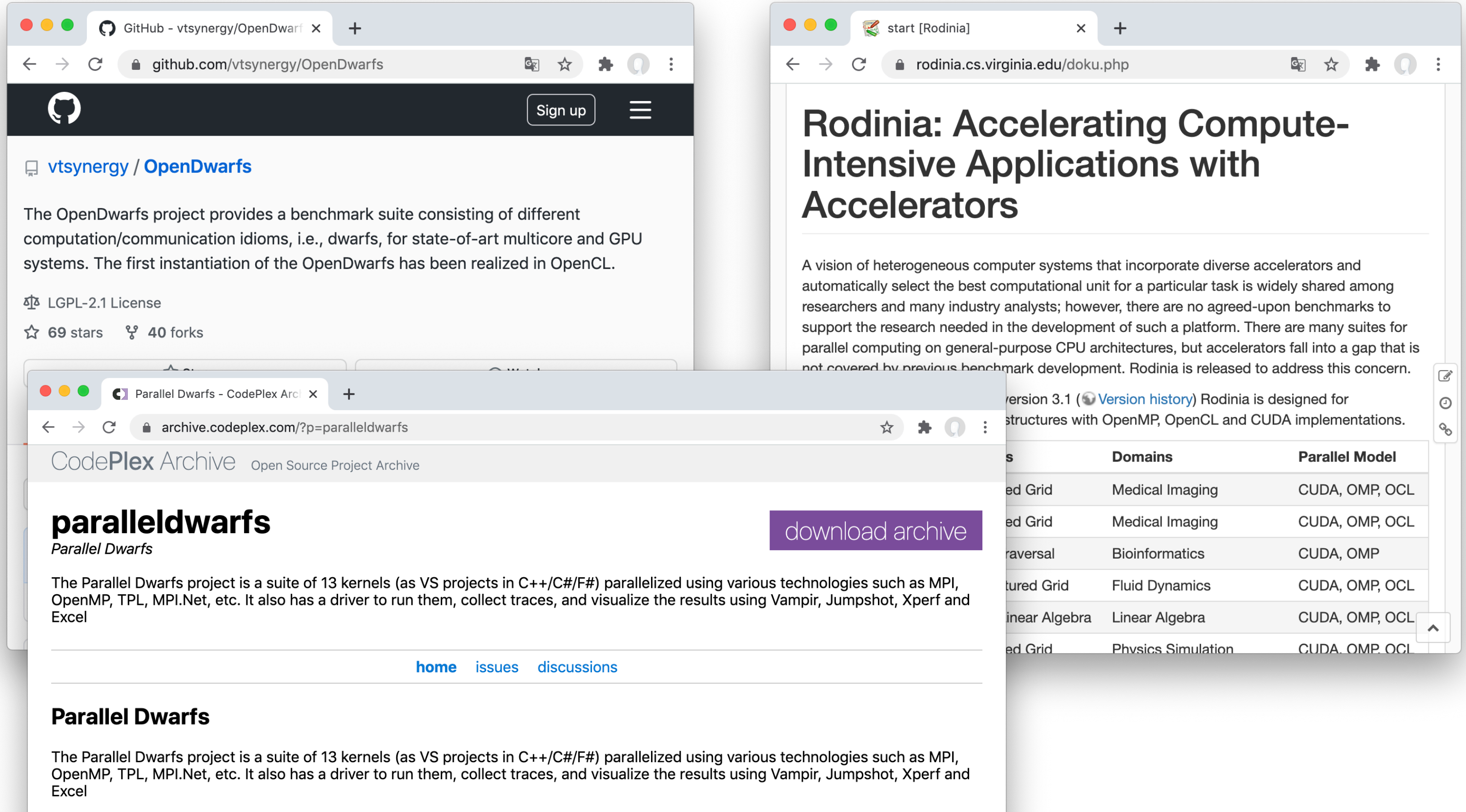
- Interconnected set of states, initial state, input, transitions (based on current inputs and state), output (based on current inputs and state)

- Parallelism in the computation of state transitions
- Decomposing into multiple state machines possible
  - Smaller and simpler
  - Combined states and outputs functionally mimic the original
  - Communication/synchronization required



- Issue: Wasted resources mapping 1 state = 1 thread (just one state possible), may not justify communication overhead
- Optimization: Decomposition, multiple FSM at the same time (case-statements within)

Exemplary Reference Implementations



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