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Narodowa Infrastruktura Superkomputerowa dla **EuroHPC**

Simulating and visualizing quantum architectures

Łukasz Pawela, IITiS PAN

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Rzeczpospolita Polska

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Motivation

- Dynamically developing
- Plethora of potential applications
- Strong interest from bussiness partners

Benefit

Easier access for business and research customers to quantum architectures

Simulators: reducing the cost of solution preparation and testing

Future-proofing: the ability to prepare solutions that work on upcoming quantum architectures

Visualizations: facilitating the design of solutions, preparation and analysis of programs

Quantum annealing

Ising model

Given a function

$$H(s) = -\sum_{i\in\mathcal{I}} h_i s_i - \sum_{(i,j)\in\mathcal{I}\times\mathcal{I}} J_{ij} s_i s_j,$$

where

$$s = [s_i]_{i\in\mathcal{I}} \in \{-1, 1\}^{\mathcal{I}}, h_i \in \mathbb{R}, J_{ij} \in \mathbb{R}.$$

The goal is to find

$$s^\star = \min_s H(s).$$

The so-called ground state

Quantum adiabatic protocol

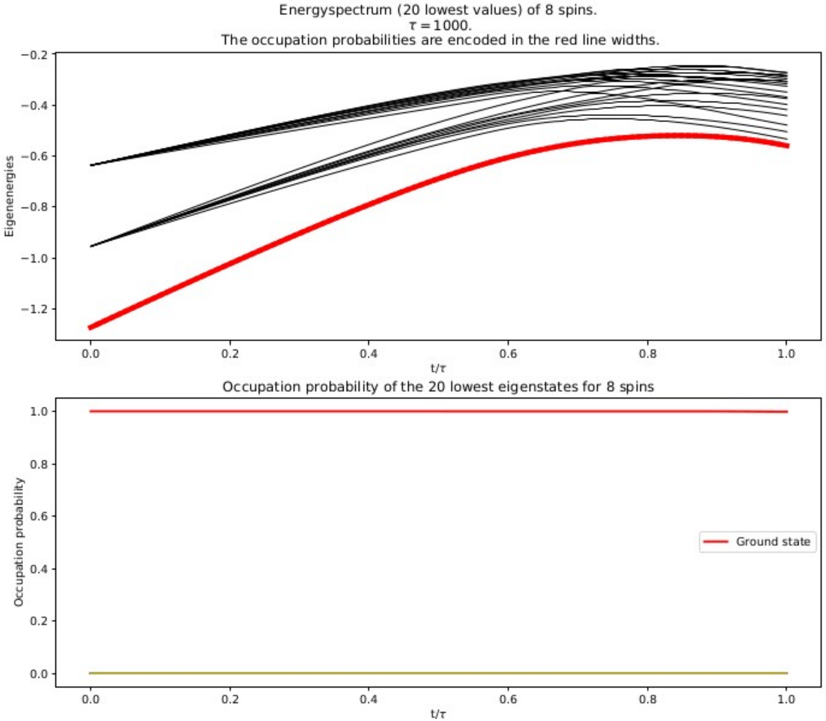
Initial Hamiltonian

$$H_0 = -\sum_{i \in \mathcal{I}} h_i \sigma_x^{(i)}.$$

Time dependent Hamiltonian

$$H(t) = \left(1 - \frac{t}{\tau}\right) H_0 + \frac{t}{\tau} H_p$$

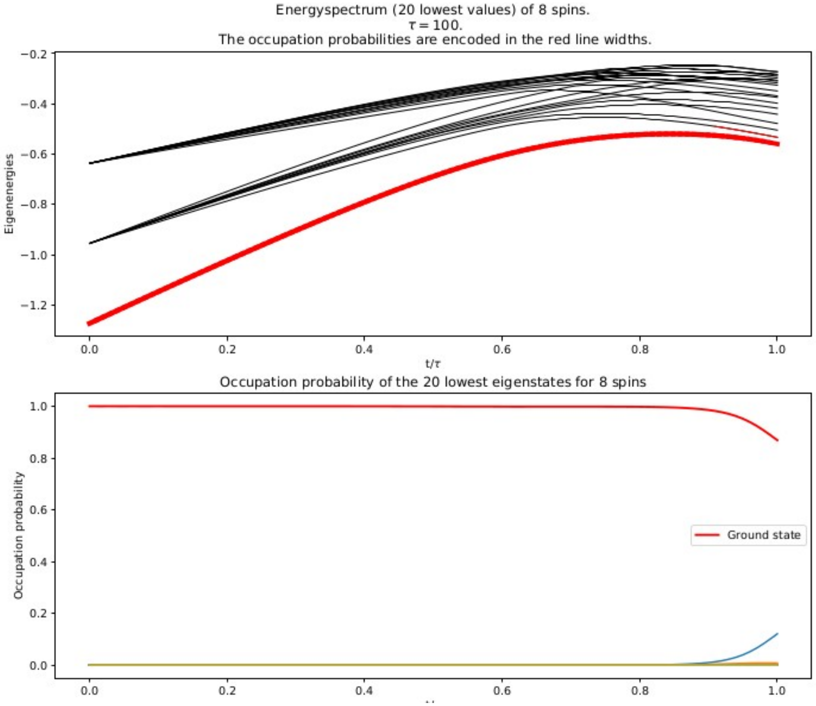
Adiabatic evolution - example



Energyspectrum (20 lowest values) of 8 spins.
$\tau = 1000$.
The occupation probabilities are encoded in the red line widths.

Occupation probability of the 20 lowest eigenstates for 8 spins

Adiabatic evolution - example



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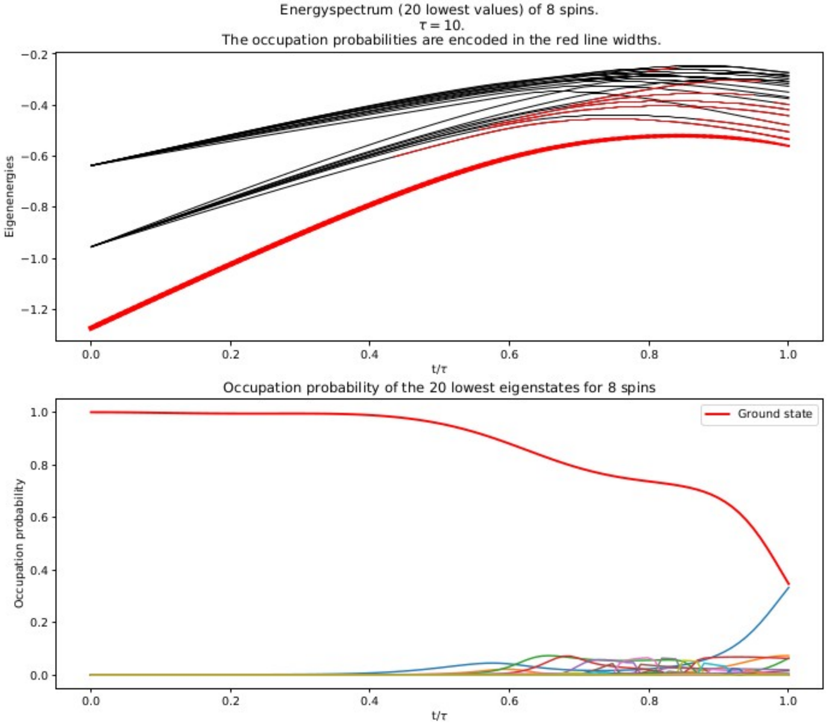
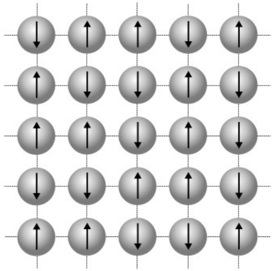
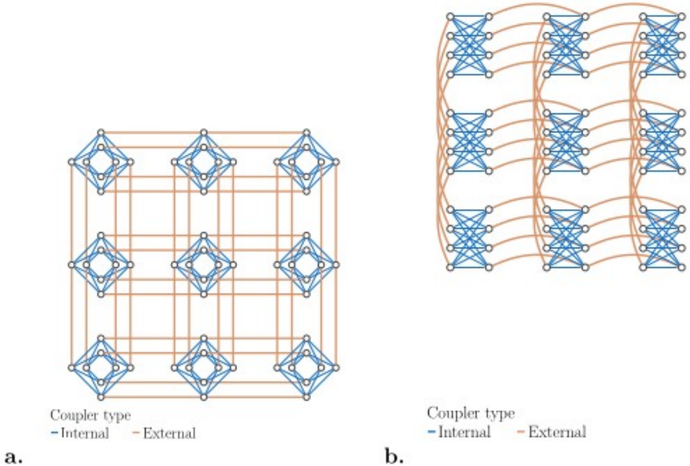
Adiabatic evolution - example



Simulating annealing of spin glasses

Spin glass simulation

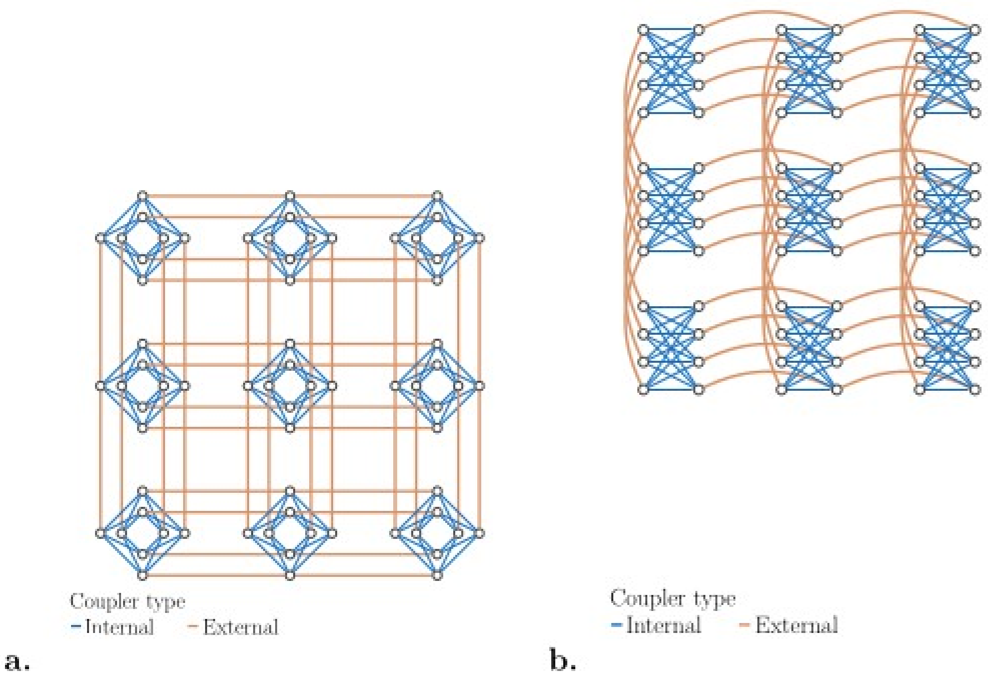




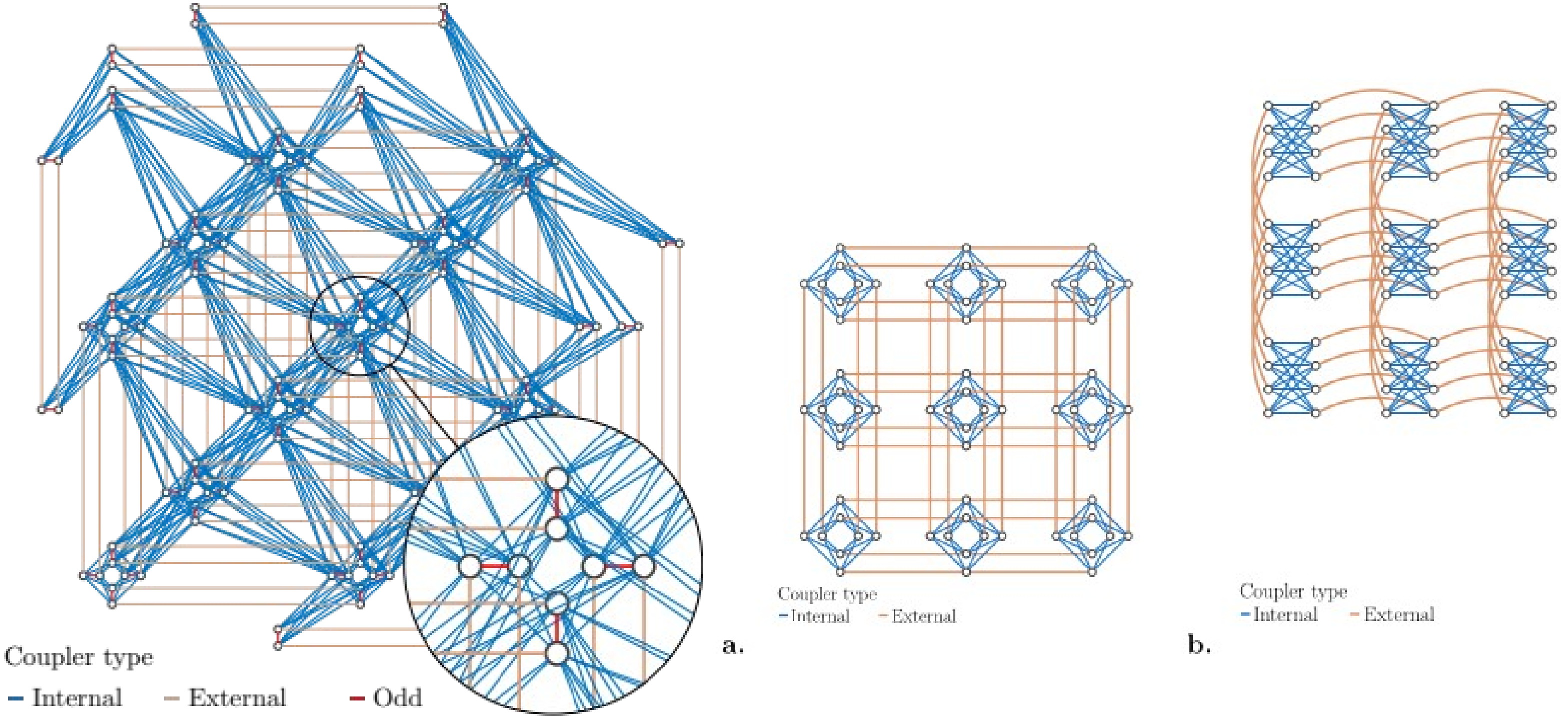
$$H(s) = -\sum_{i\in\mathcal{I}} h_i s_i - \sum_{(i,j)\in\mathcal{I}\times\mathcal{I}} J_{ij} s_i s_j ,$$

$$s = [s_i]_{i\in\mathcal{I}} \in \{-1,1\}^{\mathcal{I}},\, h_i \in \mathbb{R},\, J_{ij} \in \mathbb{R}$$

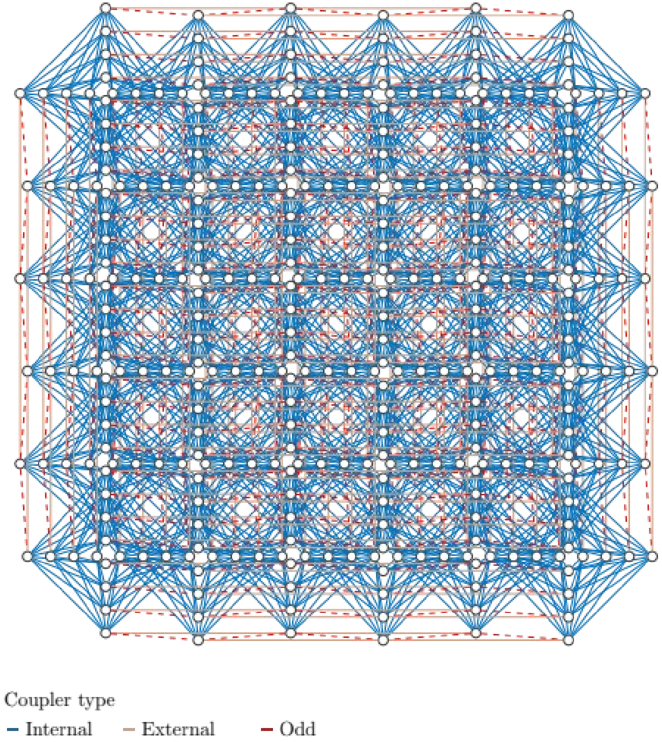
$$s^\star = \arg\min_s H(s).$$


Coupler type
Internal
External
a.
Coupler type
Internal
External
b.

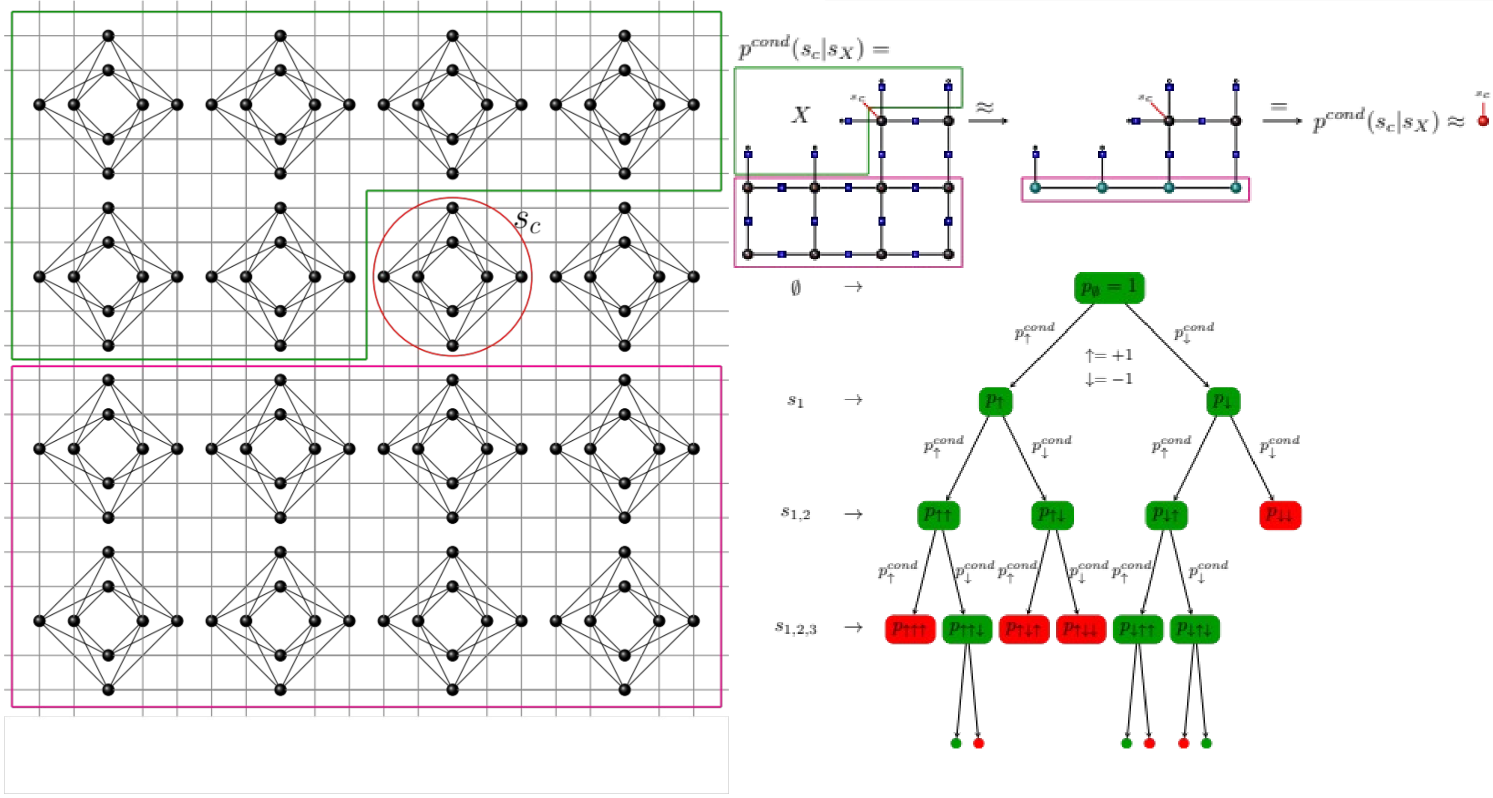
D-Wave Pegasus



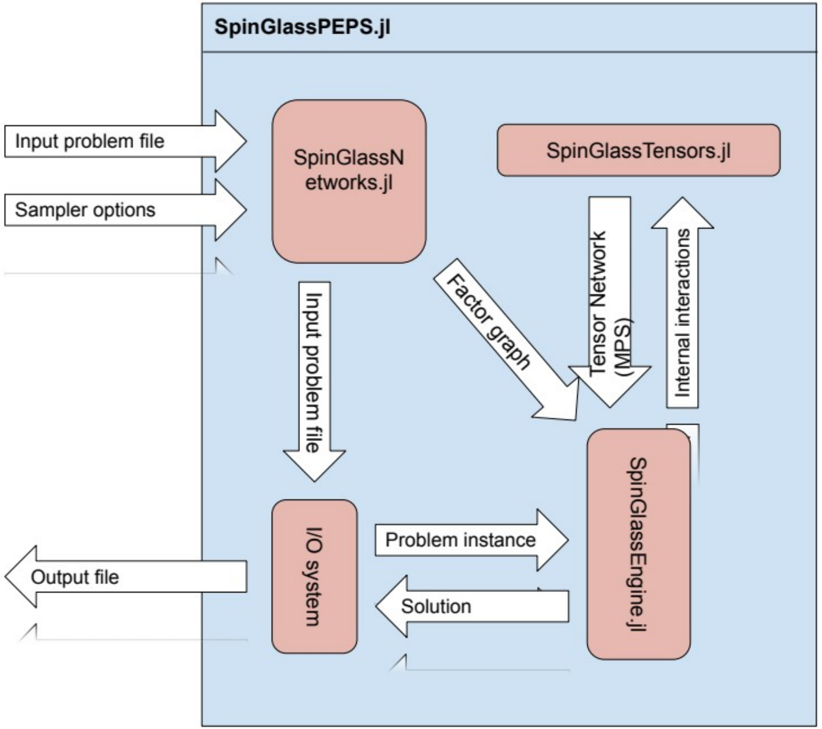
D-Wave Zephyr



Tensor networks

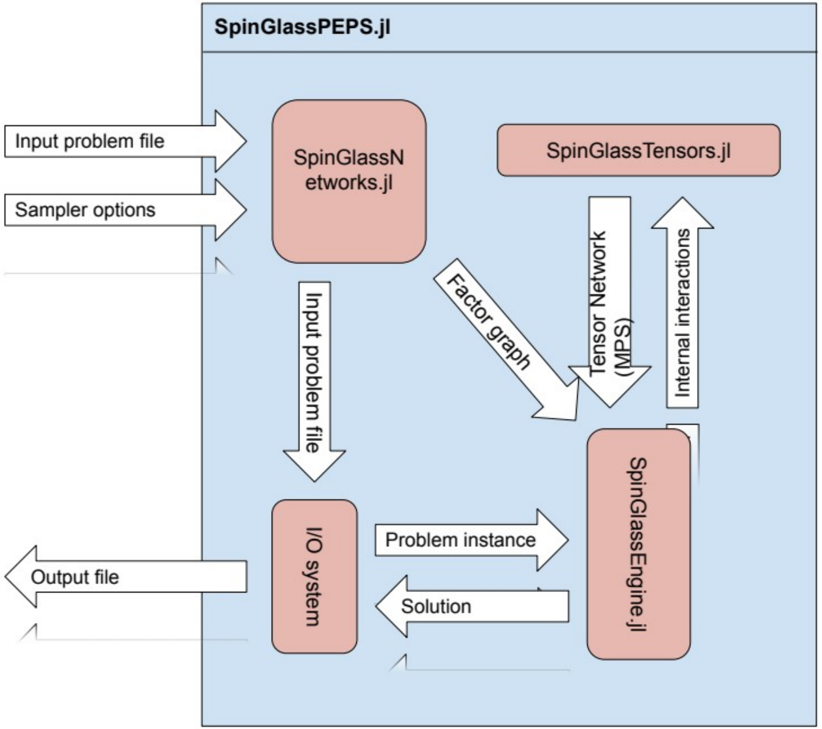

s_c
$p^{cond}(s_c|s_X) =$
X
s_c
$\approx$
s_c
$=$
$p^{cond}(s_c|s_X) \approx$
s_c
$\emptyset$ →
$p_\emptyset = 1$
$p^{cond}_\uparrow$
$p^{cond}_\downarrow$
$\uparrow = +1$
$\downarrow = -1$
s_1 →
$p_\uparrow$
$p_\downarrow$
$p^{cond}_\uparrow$
$p^{cond}_\downarrow$
$p^{cond}_\uparrow$
$p^{cond}_\downarrow$
$s_{1,2}$ →
$p_{\uparrow\uparrow}$
$p_{\uparrow\downarrow}$
$p_{\downarrow\uparrow}$
$p_{\downarrow\downarrow}$
$p^{cond}_\uparrow$
$p^{cond}_\downarrow$
$p^{cond}_\uparrow$
$p^{cond}_\downarrow$
$p^{cond}_\uparrow$
$p^{cond}_\downarrow$
$s_{1,2,3}$ →
$p_{\uparrow\uparrow\uparrow}$
$p_{\uparrow\uparrow\downarrow}$
$p_{\uparrow\downarrow\uparrow}$
$p_{\uparrow\downarrow\downarrow}$
$p_{\downarrow\uparrow\uparrow}$
$p_{\downarrow\uparrow\downarrow}$

Simulation of spin glass annealing



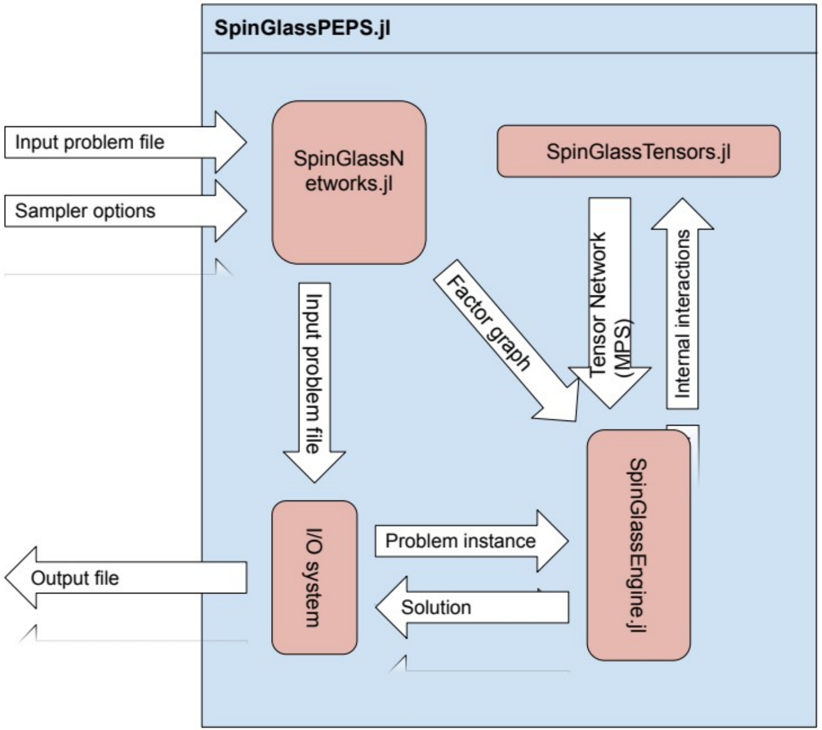
SpinGlassTensors.jl

- Tensor structures
- Opeation on tensors
- GPU utilization



SpinGlassNetworks.jl

- Network graphs
- Factor graphs
- Basic I/O



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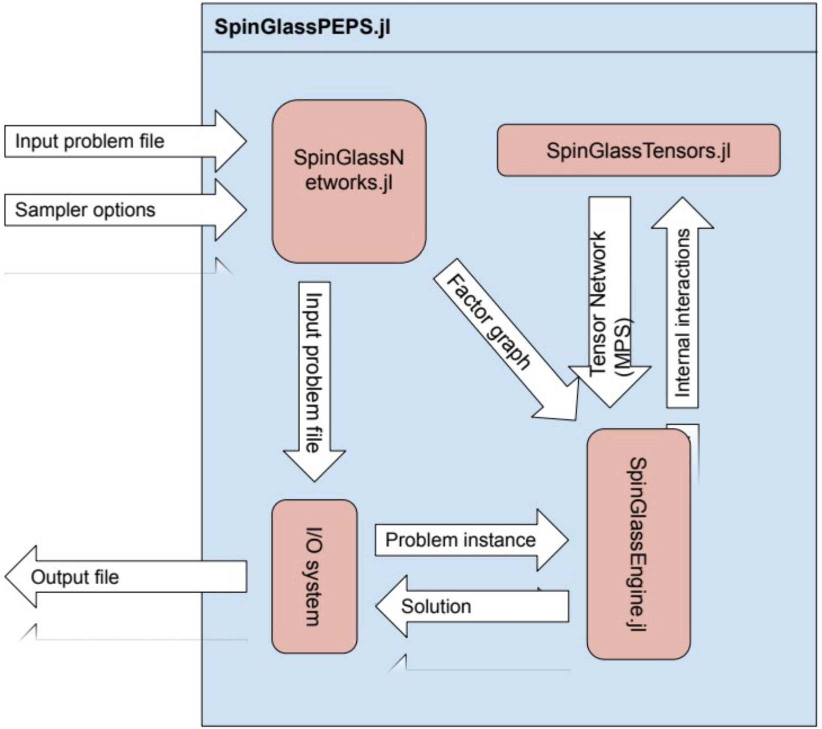
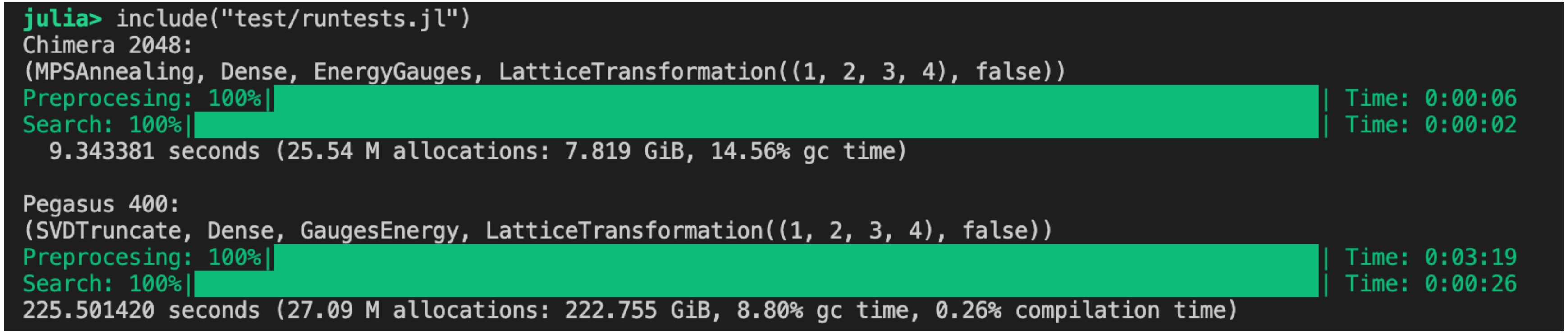
SpinGlassEngine.jl

- Main algorithms
- Efficient simulation of Chimera
- Possibility to simulate more complex structures



SpinGlassEngine.jl

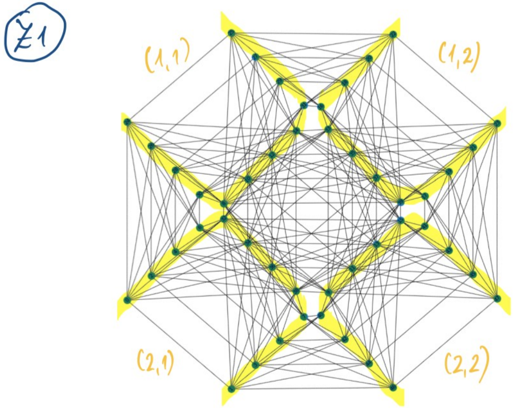


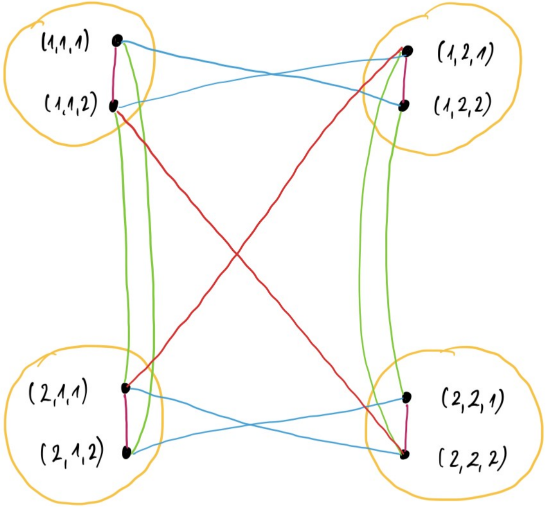
```
julia> include("test/runtests.jl")
Chimera 2048:
(MPSAnnealing, Dense, EnergyGauges, LatticeTransformation((1, 2, 3, 4), false))
Preprocesing: 100%|██████████████████████████████████████████| Time: 0:00:06
Search: 100%|██████████████████████████████████████████████████| Time: 0:00:02
  9.343381 seconds (25.54 M allocations: 7.819 GiB, 14.56% gc time)

Pegasus 400:
(SVDTruncate, Dense, GaugesEnergy, LatticeTransformation((1, 2, 3, 4), false))
Preprocesing: 100%|██████████████████████████████████████████| Time: 0:03:19
Search: 100%|██████████████████████████████████████████████████| Time: 0:00:26
225.501420 seconds (27.09 M allocations: 222.755 GiB, 8.80% gc time, 0.26% compilation time)
```

SpinGlassEngine.jl

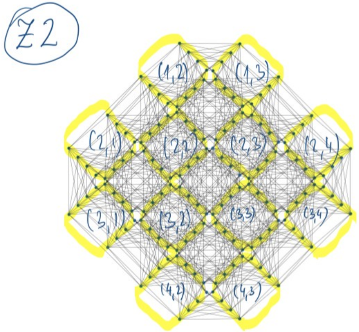
Solution: sparse tensor networks on the GPU

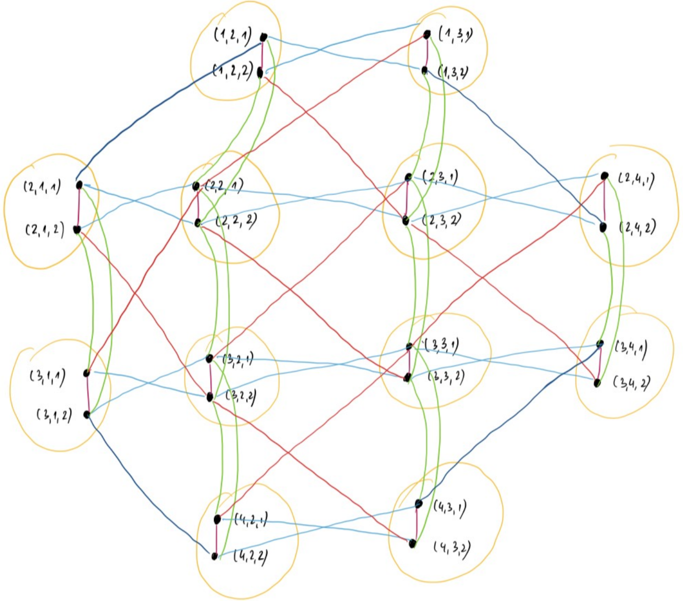




SpinGlassEngine.jl

Solution: sparse tensor networks on the GPU





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Bruteforce search

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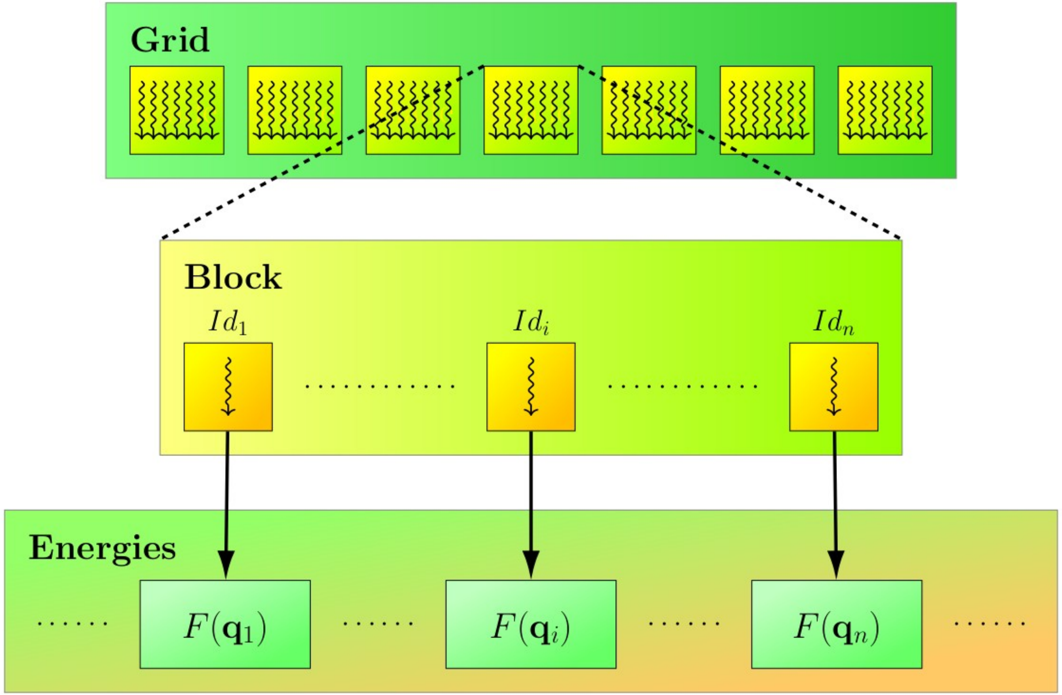
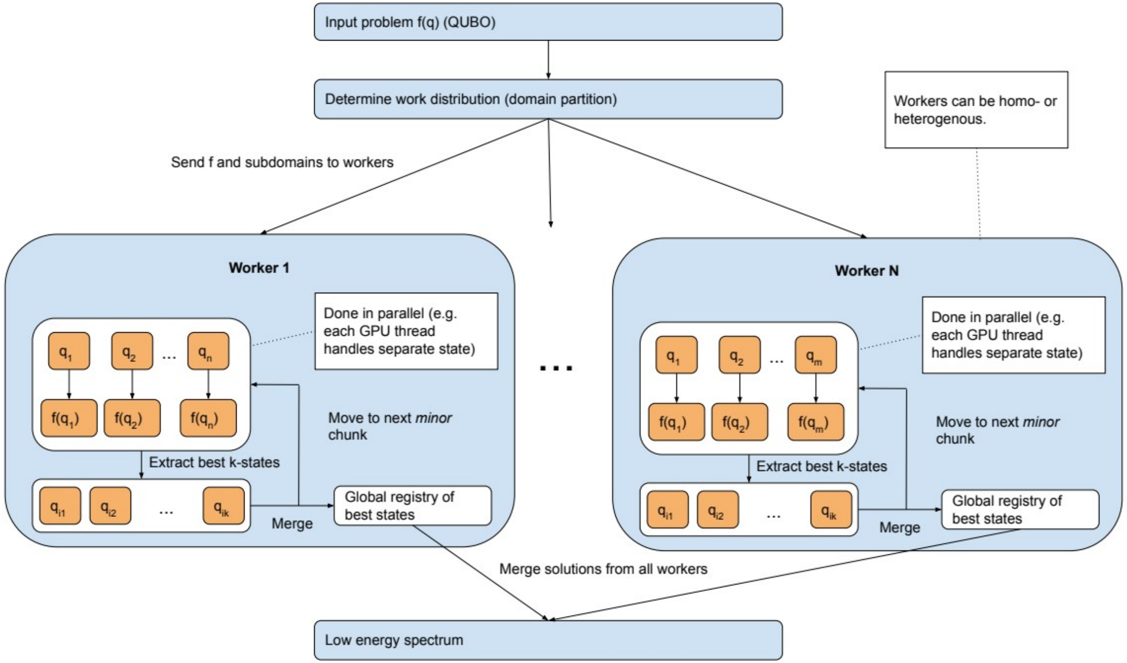
Bruteforce search



SpinGlassExhaustive.jl, omnisolver-bruteforce

- Parallel GPU implementation
- Two appraoches:
    - naive brute-force
    - Gray codes
- Main problem: parallel Sorting on the GPU


Input problem f(q) (QUBO)
Determine work distribution (domain partition)
Workers can be homo- or heterogenous.
Send f and subdomains to workers
Worker 1
q_1
q_2
...
q_n
$f(q_1)$
$f(q_2)$
$f(q_n)$
Done in parallel (e.g. each GPU thread handles separate state)
Move to next *minor* chunk
Extract best k-states
q_{i1}
q_{i2}
...
q_{ik}
Merge
Global registry of best states
...
Worker N
q_1
q_2
...
q_m
$f(q_1)$
$f(q_2)$
$f(q_m)$
Done in parallel (e.g. each GPU thread handles separate state)
Move to next *minor* chunk
Extract best k-states
q_{i1}
q_{i2}
...
q_{ik}
Merge
Global registry of best states
Merge solutions from all workers
Low energy spectrum

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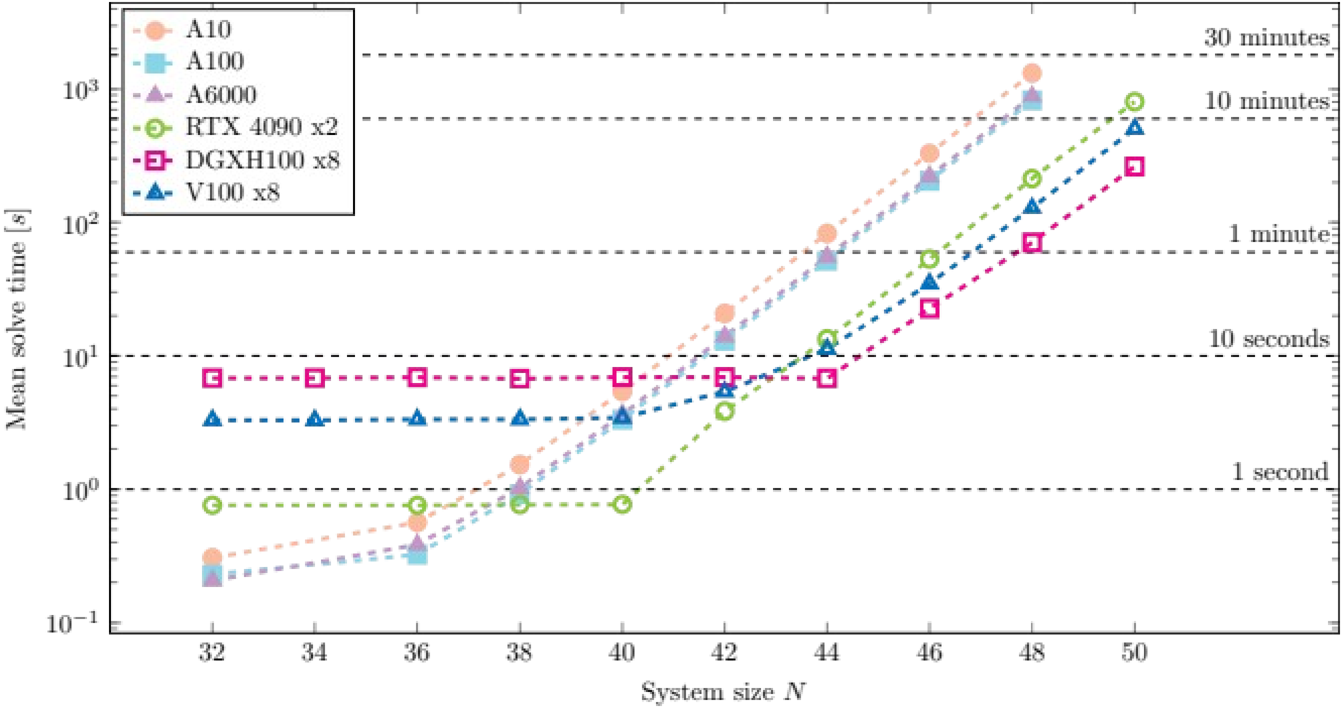
Execution times



Dynamical systems

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SpinGlassDynamics.jl

- Solving Ising instances via dynamical systems
- Main libraries:
  - DynamicalSystems.jl
  - DifferentialEquations.jl

$$y_i(t_{k+1}) = y_i(t_k) + \left\{ -\left[a_0 - a(t_k)\right] x_i(t_k) + c_0 \sum_{j=1}^{N} J_{i,j} \operatorname{sgn}\left[x_j(t_k)\right] \right\} \Delta_t \tag{17}$$

$$x_i(t_{k+1}) = x_i(t_k) + a_0 y_i(t_{k+1}) \Delta_t \tag{18}$$

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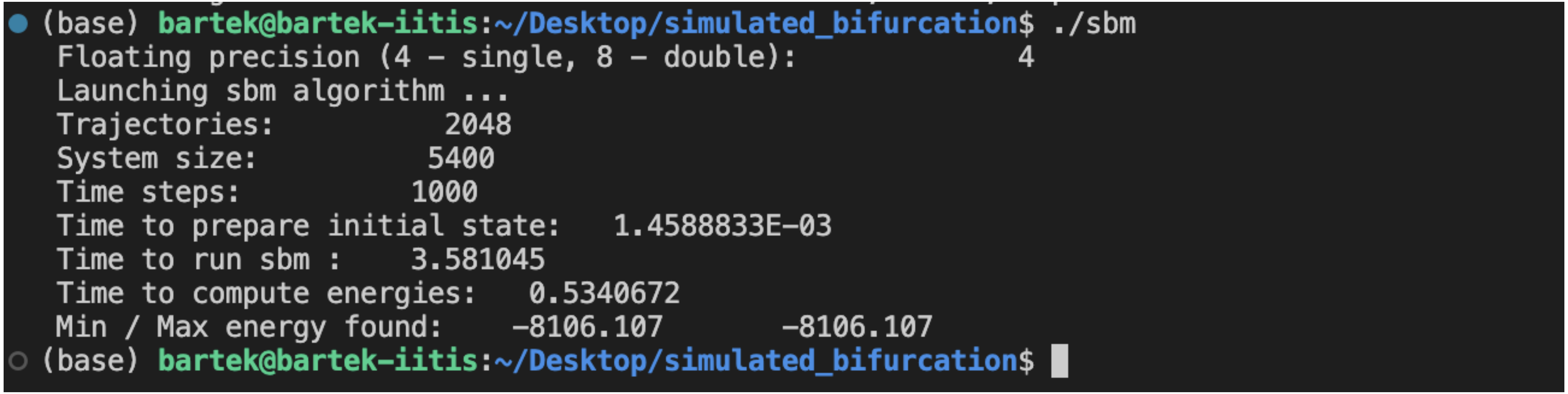
SpinGlassDynamics.jl

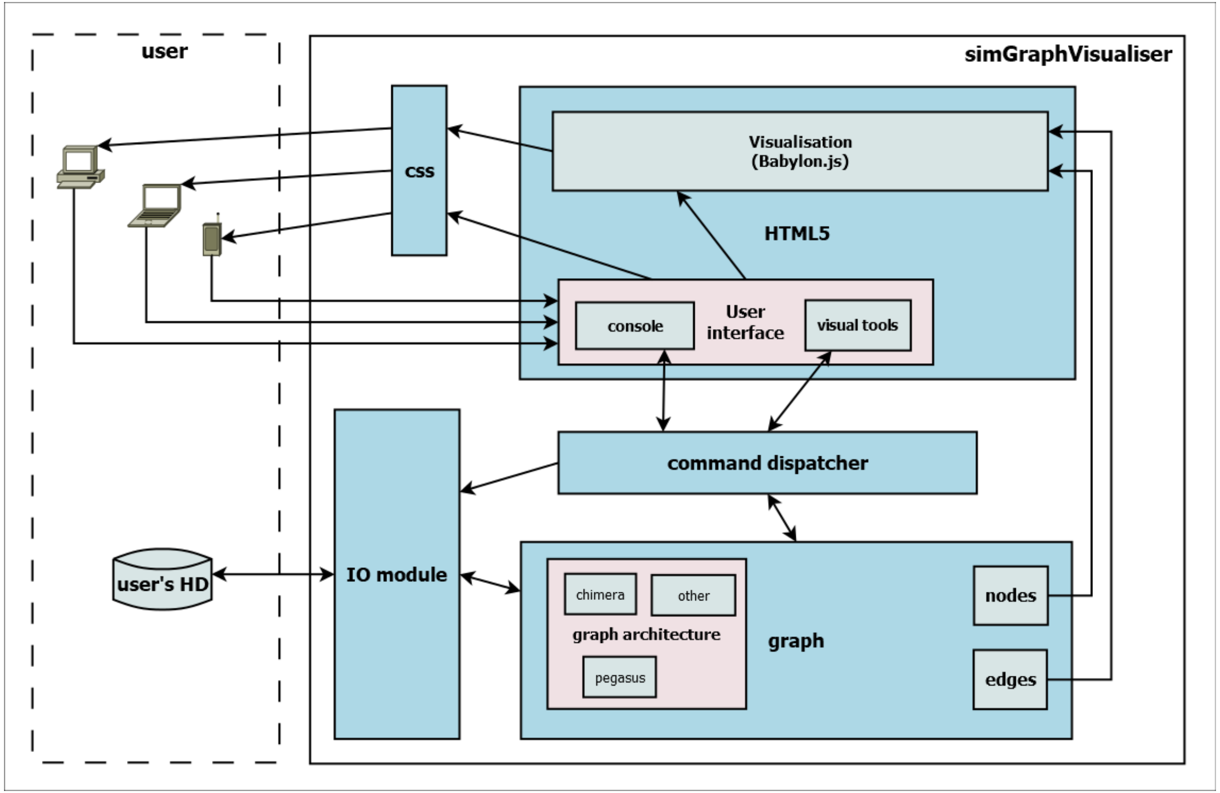
$$y_i(t_{k+1}) = y_i(t_k) + \left\{ -\left[a_0 - a(t_k)\right] x_i(t_k) + c_0 \sum_{j=1}^{N} J_{i,j} \,\mathrm{sgn}\left[x_j(t_k)\right] \right\} \Delta_t \tag{17}$$

$$x_i(t_{k+1}) = x_i(t_k) + a_0\, y_i(t_{k+1})\, \Delta_t \tag{18}$$



```
● (base) bartek@bartek-iitis:~/Desktop/simulated_bifurcation$ ./sbm
   Floating precision (4 - single, 8 - double):             4
   Launching sbm algorithm ...
   Trajectories:           2048
   System size:           5400
   Time steps:           1000
   Time to prepare initial state:   1.4588833E-03
   Time to run sbm :     3.581045
   Time to compute energies:   0.5340672
   Min / Max energy found:    -8106.107        -8106.107
○ (base) bartek@bartek-iitis:~/Desktop/simulated_bifurcation$ 
```

Visualization



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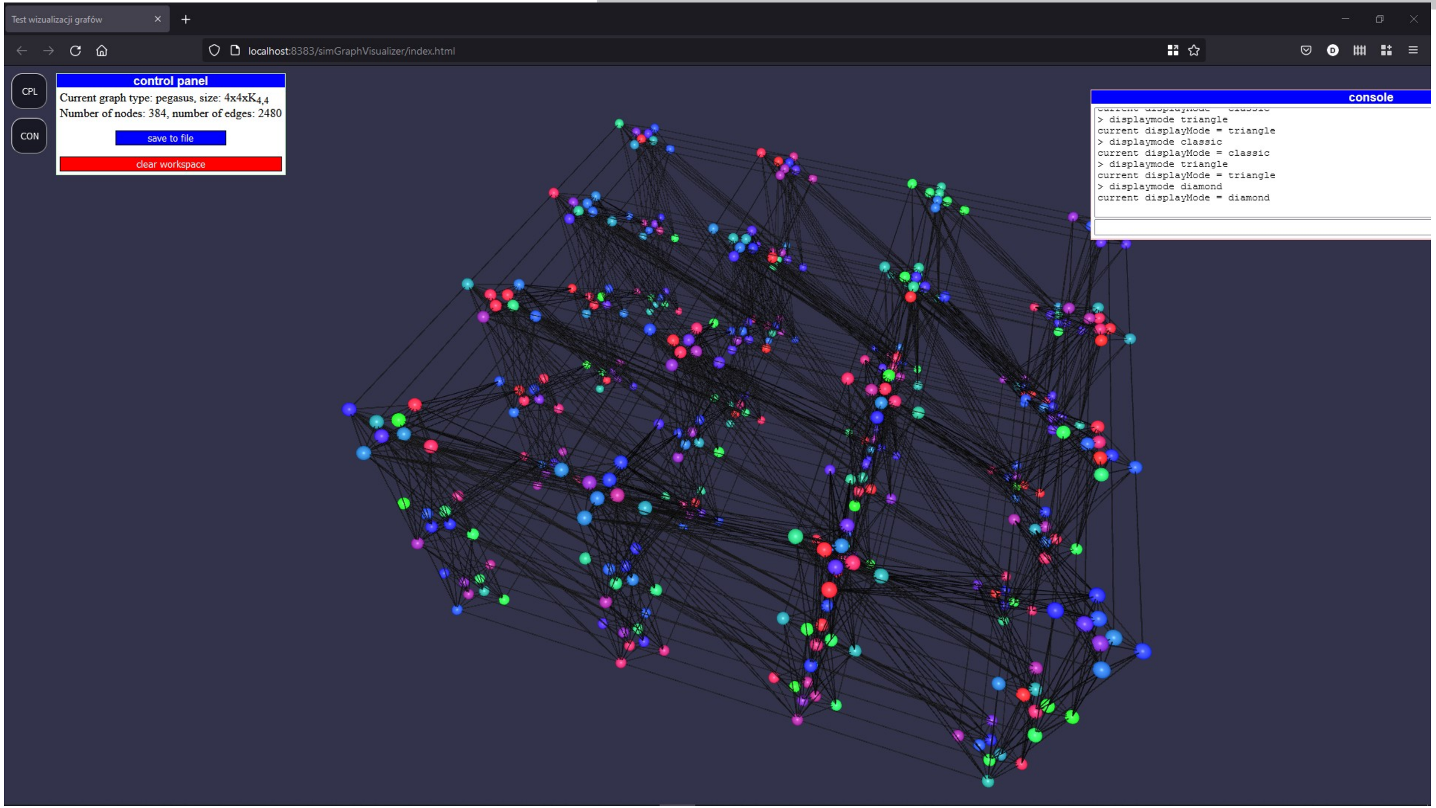
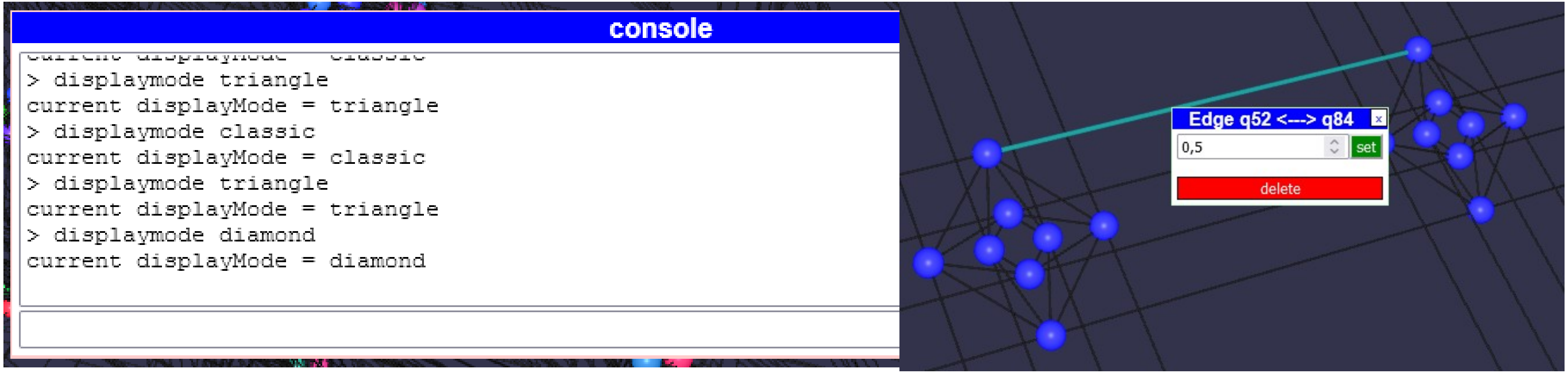


Current graph type: pegasus, size: $4x4xK_{4,4}$

Number of nodes: 384, number of edges: 2480

```
current displayMode = classic
> displaymode triangle
current displayMode = triangle
> displaymode classic
current displayMode = classic
> displaymode triangle
current displayMode = triangle
> displaymode diamond
current displayMode = diamond
```

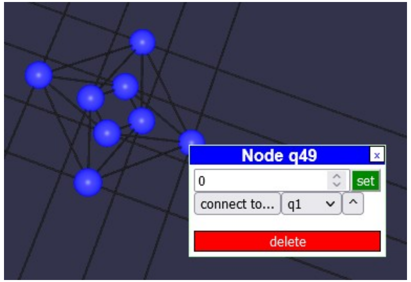


console

```
current displayMode = classic
> displaymode triangle
current displayMode = triangle
> displaymode classic
current displayMode = classic
> displaymode triangle
current displayMode = triangle
> displaymode diamond
current displayMode = diamond
```

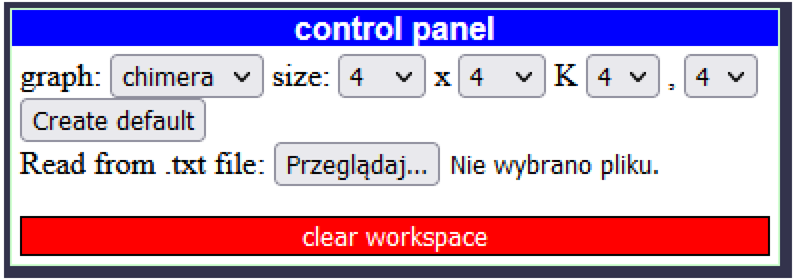
Edge q52 <---> q84

0,5



Node q49

0



control panel

graph: chimera size: 4 x 4 K 4 , 4

Read from .txt file: Przeglądaj... Nie wybrano pliku.

THANK YOU

Repositories

- https://github.com/euro-hpc-pl/SpinGlassPEPS.jl
- https://github.com/euro-hpc-pl/omnisolver-bruteforce
- https://github.com/euro-hpc-pl/SpinGlassDynamics.jl

Publication:
arXiv:2112.11131

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