

Evolutionary Mechanics

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Abstract

We developed an application that is able to develop mechanical structures using an evolutionary algorithm. This approach can be scaled efficiently across many different nodes.

1 Method

Our project is divided in two sections and corresponding layers of parallelism. The first one is solving the mechanical equations to check if a mechanical structure can withstand a force. Figure 1 shows the result of such a simulation. The shape of a figure is approximated through squares.

The second stage is the evolutionary algorithm. The best 10% survive in each round. The structures mutate and are simulated again. Even though we put a lot of effort into parallelizing the equation solver, it turned out, that in the end it is faster to parallelize just the evolutionary algorithm instead of parallelizing the evolutionary algorithm and the equation solver. This is, because the core count is usually lower than the generation size, which means that each core can process its own structure.

1.1 Speeding up the equation solver

`OpenMP` is used for parallelizing the equation solver. The reason for that is the tight coupling between the data. `gprof` revealed that the equation solver spends most of its time in the sparse matrix multiplication, however the whole equation solver class works parallelized.

- The equation setup process adds the local element stiffness matrix into the global equation system. Depending on the mechanical structure, the position of different planes appears rather random. Therefore, a lock is needed to prevent a race condition. Because the matrix is sparse and each thread works on its own plane, that typically are not directly connected, it is improbable that two threads operate on the same equation row at the same time. A global lock would introduce an unnecessary penalty, therefore each row uses its own lock.
- All linear algebra operations work in parallel. There are two types of these operations. In Addition, scalar multiplication, matrix multiplication or assigning a constant value,

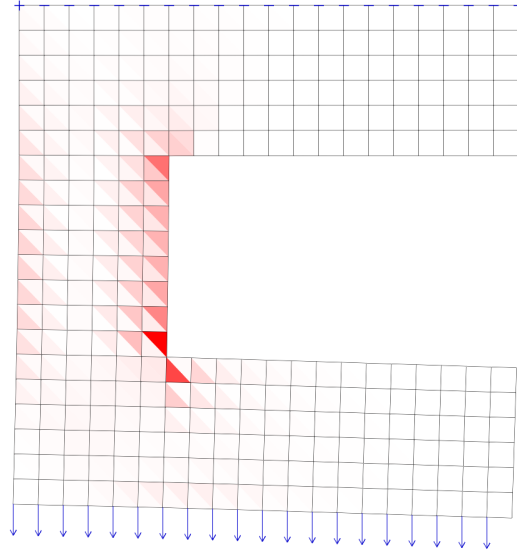


Figure 1: Result of a mechanical simulation

each thread processes its own chunk of rows. This means, that these operations do not require an implicit or explicit barrier. If for example, a vector addition follows a scalar multiplication, it is fine if the first thread begins with the scalar multiplication before the second thread has finished the vector addition, since each of them operates on its own set of rows.

However, in the conjugate gradient method there are also operations like the scalar product or the norm of the vector. These operations require a reduction and have an implicit barrier.

- In the beginning, a unique index has to be assigned to each Plane and corner. This is not parallelizable, as the total number of planes and corners is unknown and does not follow a predictable pattern.

The equation solver has theoretically strong scalability, as the dominant part in the computational complexity, the sparse matrix multiplication, can be split according to rows. In practice however, there is a significant overhead in creating the threads. This means, that the speedup becomes only notable for problem sizes above 50.

Also, the evolutionary algorithm easily solves several thousand equation systems per second, and for the problem sizes that we evaluated the algorithm on, the thread creation becomes the significant overhead. So while the program is still capable of utilizing multiple cores for solving the equation, we rather decided to let each core process one or multiple structures per generation.

Nevertheless, the Equation Solver is a powerful solver, that scales well with core-count. It is able to solve a mechanical structure that consists of 80600 equations in 2.732s using 28 cores on bridges. It also showcases OpenMP and locks well, we therefore decided to leave the code there. The speedup is shown in figure 3.

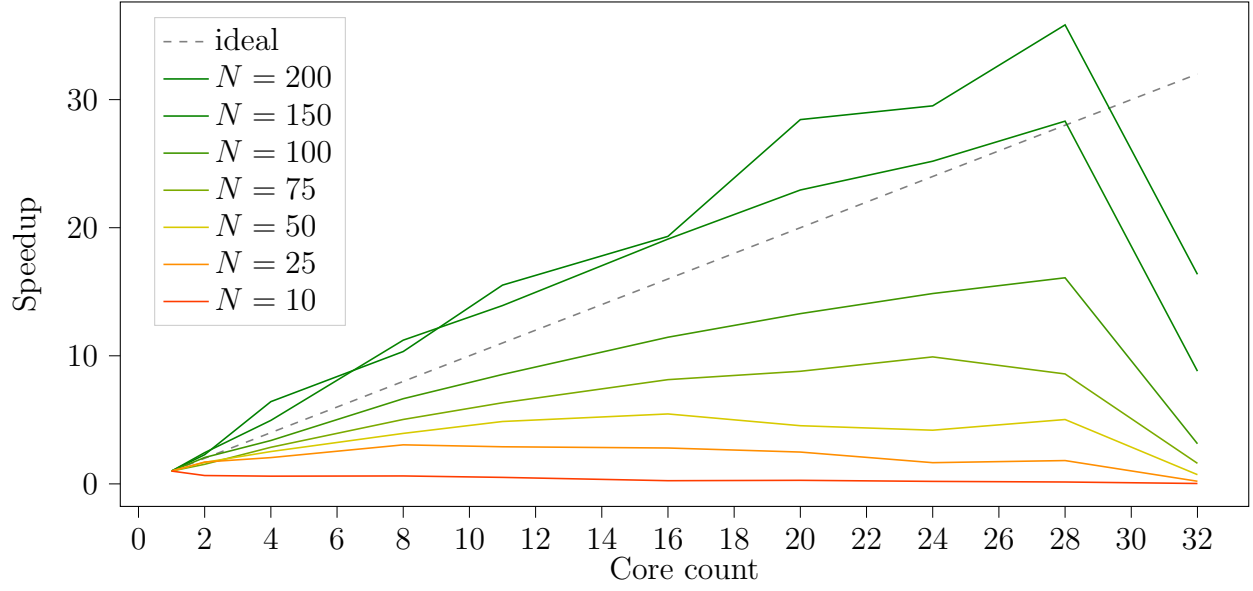


Figure 2: Speedup of the equation solver for different problem sizes N .

	$N = 10$	$N = 25$	$N = 50$	$N = 75$	$N = 100$	$N = 150$	$N = 200$
Equations	230	1325	5150	11475	20300	45450	80600
$C = 1$	3	43	311	1153	3306	19869	97932
$C = 2$	4	25	185	754	1604	8149	42934
$C = 4$	5	21	123	403	976	4008	15251
$C = 8$	5	14	79	229	497	1771	9477
$C = 11$	6	15	64	182	387	1427	6311
$C = 16$	11	15	57	142	289	1040	5067
$C = 20$	10	17	69	131	249	866	3443
$C = 24$	14	26	74	116	222	789	3318
$C = 28$	19	24	62	134	205	702	2733
$C = 32$	91	209	432	718	1055	2257	5986

Table 1: Execution time for the equation solver for different field sizes N and cores C

1.2 Speeding up the evolutionary algorithm

Evolutionary algorithms are very parallel by nature. Each organism can be evaluated independent. Then they have to be sorted. We do the sorting on a node 0. **Gather** is used in that process. The best 10% get redistributed using **Bcast**.

A MPI Message for an evaluated board consists of

- 1 float for the score
- $R \times C$ bytes, each containing the boolean value of the field.

We typically simulate grid sizes of 20, meaning the message has a size of 404 bytes. Since all processes will be initialized with the same field size it has not to be stored in the message. Our evolution works like shown in algorithm 1. The result of the finished evolution is shown on figure 4.

Algorithm 1 Evolute on node

```
Initialize all local fields fully set
for all epochs do
  Mutate the fields
  Evaluate the fields
  Gather all fields into the master
  Sort the fields on the master
  Broadcast the best 10% to everyone
  Replace local fields
end for
```

Cores	7	14	28	56	112	224
Cores per Task	1	1	1	1	1	2
Tasks	7	14	28	56	112	112
Nodes	1	1	1	2	4	8
<hr/>						
N = 10	33.667	(16.263)	9,399	5.432	2.950	4.256
N = 20	296.997	(196.137)	91.958	43.114	25.199	29.429
N = 40	(2686.816)	(1343.408)	(671.704)	335.852	200.529	164.243

Table 2: Execution time in seconds for the evolution for different field sizes N and cores C . The generation size is set fixed to 112 and 1000 epochs are simulated.

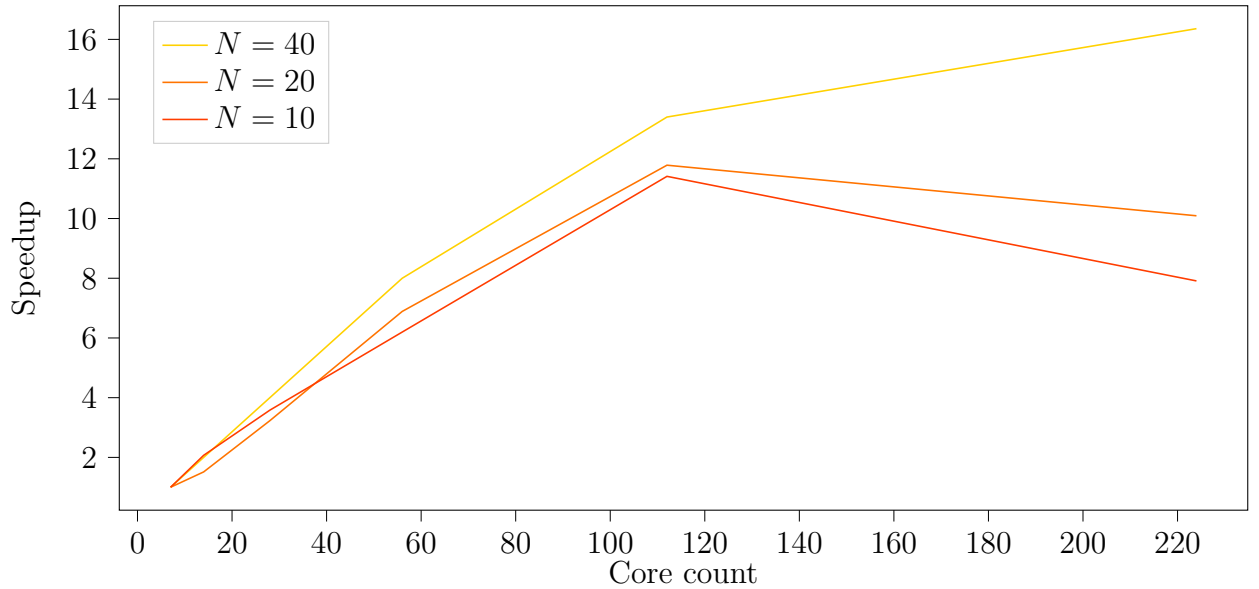


Figure 3: Speedup of the equation solver for different problem sizes N .

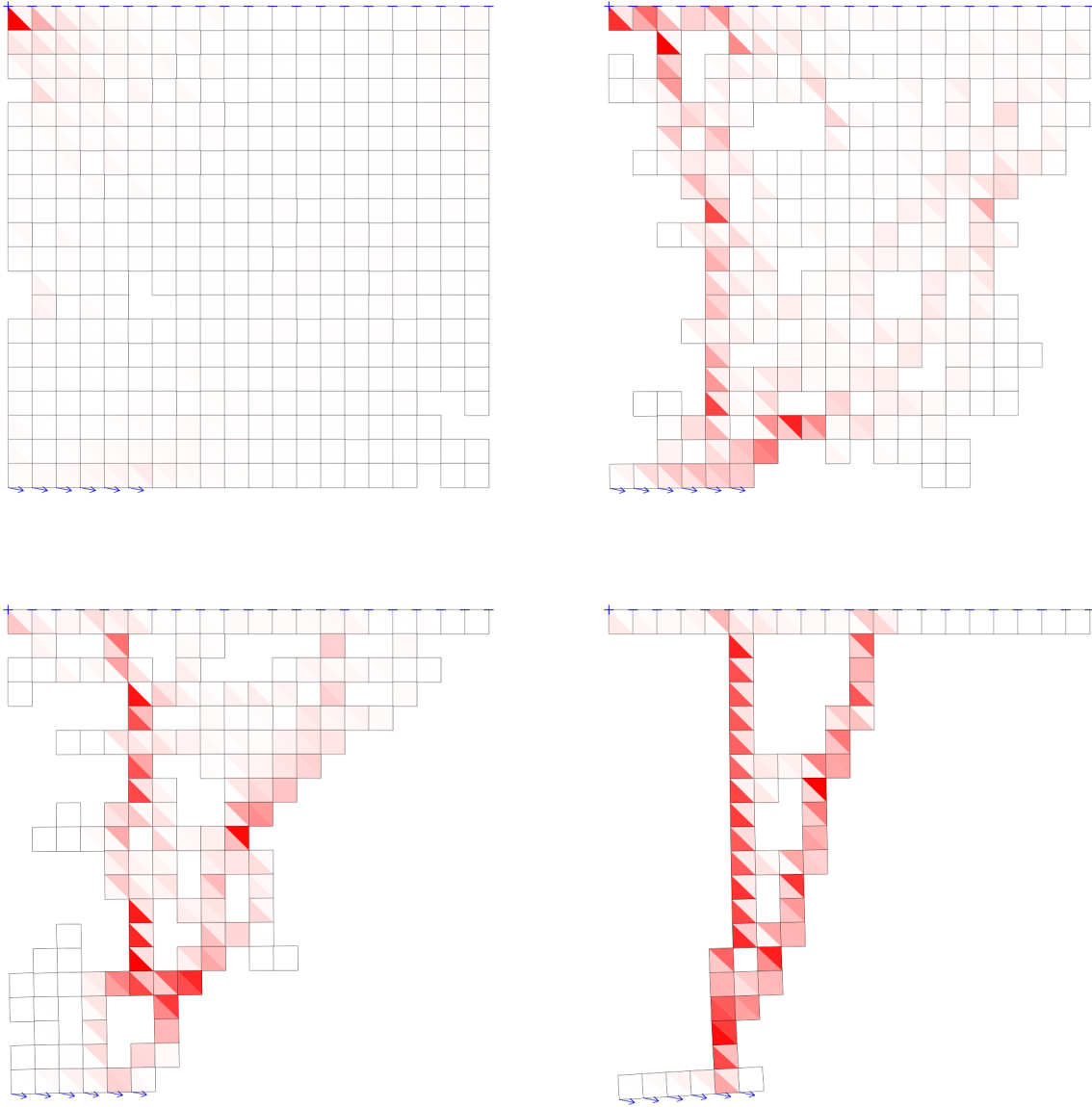


Figure 4: Result of a evolution, using 20×20 grid, 100 organisms per epoch, 1000 epochs and a alterations decay of 0.995. Note, how the structure gets wider on the top to deal with the increased bending stress.