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Porównanie silników fizyki 3D

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OŚWIADCZENIE AUTORA PRACY

Oświadczam, świadomy odpowiedzialności karnej za poświadczenie nieprawdy, że niniejszą pracę dyplomową wykonałem osobiście i samodzielnie, i nie korzystałem ze źródeł innych niż wymienione w pracy.

.....
PODPIS

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Master of Science Thesis

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Comparison of 3D physics engines

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Serdecznie podziękowania dla ...

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1. Introduction

The main objective of presented project is the implementation of parts of 3D engine in a browser environment. Parts of engine are analysed side-by-side with parallel engine compiled from C++. The objective of analysis is comparison of performance and description of possible issues related to the limited browser resources and dynamic features of JavaScript.

Browser-based engine is implemented in JavaScript and analyzed in V8 engine. V8 is maintained by Google and is used in Google Chrome browser. Executable examples are compiled using gcc compiler and are runned on the same platform. For additional comparison Emscripten project is used to automatically generate JavaScript and measure if automated conversion may be as effective as writing code by hand.

Project is based on conference sessions and announcements authored by V8 programmers regarding performance of JavaScript applications. Analysis of available materials is a topic of Chapter 2, where internals of modern engines for dynamic languages are briefly explained.

Chapter 3 covers particles system found often in graphic engines. It shows techniques related to memory allocation and garbage collection that help to improve performance. Two particle systems are presented - one with high memory allocation that is expected to cause some performance issues and second one, improved by usage of object pools.

Chapter 4 is focused on sphere collision detection and reaction, with both naive solution and space partitioning using Octree. This benchmark shows application with high CPU usage and relatively simple math computations.

Chapter 5 describes Emscripten, project aimed to convert complete C++ projects to JavaScript. Related library, asm.js, is presented with overview of architectural choices that lead to better performance. Generated code is compared to the one created in previous chapters and execution times of all benchmarks is compared and briefly explained.

Last chapter is summary of all achieved results. Limitations of JavaScript engines are presented alongside future possibilities for gaming industry.

Benchmarks are by no means a complete physics system and are not representing current state of the art of physics algorithms. They are aimed to resemble optimal algorithms in used methods and complexity, so that benchmarks reflect how actual engine is using memory and computing power.

2. Overview of JavaScript and V8 engine architecture

At present JavaScript is only language widely supported by all browsers. With all it's advantages and quirks is the only choice available for programmers.¹ It was developed in 1995 as NetScape browser's solution for more dynamic web pages.

Historically, JavaScript was considered untyped language, meaning that values had no types attached to variables, either by programmer or compiler. All variables were of single, unified type and procedures called unboxing and boxing, performed before and after each operation on variable, ensured that it was properly used on machine code level. Complete code source was sent from server to the browser and was parsed and executed on fly. Without types attached to variables, all functions were polymorphic and unstable, since parameters may have carried any type of variable. To solve this problem source code of function was parsed each time it was called, each time generating machine code based on current parameters and variables in scope. This approach, called interpretation, is still present in JavaScript engines and used whenever variables don't match set criteria of stability described later in this chapter.

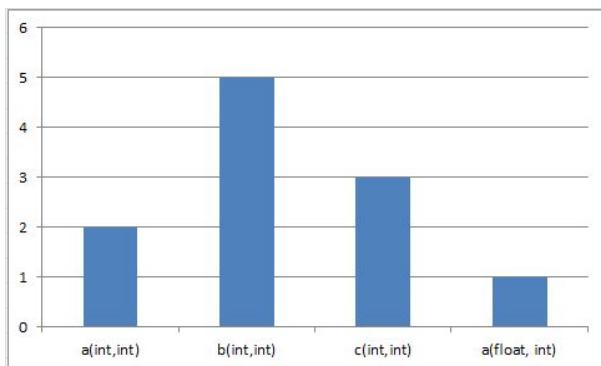
This paper uses as an engine of choice V8 Crankshaft. Choice was made because it's the only engine available at the moment which provides direct command line access, enabling precise performance measurements of code parsing and execution, without browser context and overhead. Executable file of V8 (named d8) is compiled with consideration of target platform.

¹Currently two new languages are worked on - Dart by Google and TypeScript by MicroSoft. However, to enable cross-compilation to JavaScript, paradigm of these languages is similar and work is focused mainly on better IDE support.

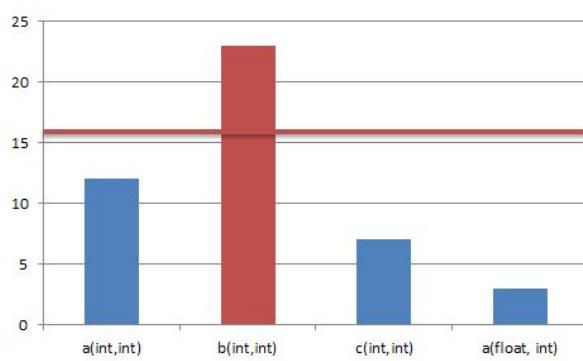
2.1. JIT compilation - tracking variable types

As mentioned before, initially JavaScript was treated as untyped language. With release of SpiderMonkey in Firefox 3.5 in 2009 situation has changed. First Just-In-Time compiler for JavaScript, TraceMonkey, was created. Based on works of Prof. Dr. Michael Franz on TraceTrees² JIT compiler was collecting all paths that interpreter took with specific types of variables. A path could split to different methods or if statements. Whenever part of code was executed often enough, path was marked as hot and compiler optimised it for given types. If single path was traversed with different set of types compiler could generate another version of optimised code. When path turned out to be highly polymorphic optimised versions were removed and interpreter was used as a fallback. Initial reports shown speedups between 20x to 40x³. However, trace JIT turned out to be very complicated to maintain⁴ and eventually was removed from Firefox in 2011.⁵ At the time SpiderMonkey was already equipped with JägerMonkey, JIT engine based on method calls. Instead of collecting complete traces, only method calls are counted. This gives easy track of function parameters and variables in scope.

Rysunek 2.1: JIT compiler tracking method calls



Rysunek 2.2: JIT compiler marking one of methods as hot and recompiling



This proved to be more effective and simpler approach and now used in all JavaScript engines. In V8 Crankshaft step forward was taken and simple methods are compiled even before any statistics on data types are collected. For compiled methods source code is not stored. Instead procedure called deoptimisation is implemented. Whenever engine detects that compiled code doesn't match actual types of variables, code is

²<http://www.michaelfranz.com/>

³<http://arstechnica.com/information-technology/2008/08/firefox-to-get-massive-javascript-performance-boost/>

⁴<https://hacks.mozilla.org/2010/03/improving-javascript-performance-with-jagermonkey/>

⁵<http://blog.mozilla.org/nethercote/2011/11/23/memshrink-progress-report-week-23/>

deoptimised and either optimised again to match new, better set of variables, or kept in interpreter friendly form.

To track these changes two debug options for V8 are available: `-trace-opt` and `-trace-deopt`.

```
1 [marking Point.setX 0x2d6ecb87e568 for recompilation,
2 reason: small function, ICs with typeinfo: 1/1 (100%)]
3 [marking Point.setY 0x2d6ecb87e5b0 for recompilation,
4 reason: small function, ICs with typeinfo: 1/1 (100%)]
5
6 [optimizing: Point.setY / 2d6ecb87e5b1 - took 0.037, 0.047, 0.000 ms]
7 [optimizing: Point.setX / 2d6ecb87e569 - took 0.021, 0.038, 0.000 ms]
8
9 [marking Point 0x2d6ecb87e448 for recompilation,
10 reason: small function, ICs with typeinfo: 0/0 (100%)]
11 [marking dot 0x2d6ecb87e490 for recompilation,
12 reason: small function, ICs with typeinfo: 7/7 (100%)]
13
14 [optimizing: Point / 2d6ecb87e449 - took 0.004, 0.019, 0.000 ms]
15 [optimizing: dot / 2d6ecb87e491 - took 0.013, 0.057, 0.000 ms]
16
17 **** DEOPT: dot at bailout #2, address 0x0, frame size 0
18 [deoptimizing: begin 0x2d6ecb87e491 dot @2]
19   translating dot => node=3, height=0
20 [deoptimizing: end 0x2d6ecb87e491 dot => node=3, pc=0x98518d30ac6, state=NO_REGISTERS,
21   alignment=no padding, took 0.146 ms]
22 [removing optimized code for: dot]
```

Listing 2.1: Output from V8 debug run showing optimisation and deoptimisation

2.2. Type interference

V8's method of optimising code before it's run relies on type inference. Based on context of variable it's type is guessed. Generated assembler has to support cache miss - whenever inferred type turns out to be incorrect, new type is assigned and another JIT compilation runs. Types of variables are organised in a tree, where Number object may store both Float or Integer, Integer may store SMI (small int), etc.

```

1 //      Unknown
2 //      |   \-----
3 //      |           |
4 //      Primitive      Non-primitive
5 //      |   \-----  |
6 //      |           |   |
7 //      Number       String  |
8 //      /   \          |   |
9 //      Double    Integer32  |   /
10 //     |           |   /   /
11 //     |           Smi   /   /
12 //     |           |   /   _/
13 //           Uninitialized.

```

Listing 2.2: Tree of types in JavaScript

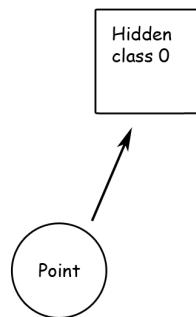
In V8 type inference is tightly connected with JIT compilation and may be tracked with the same flags: `-trace-opt` and `-trace-deopt`.

2.3. Hidden classes

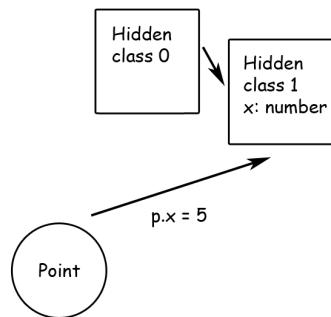
TODO: add paragraph on dictionary mode in objects.

JavaScript is classless language. Object may have defined a prototype which behaves similar to base class in other languages. However, a property may be added to an Object or its prototype at any point in runtime. To optimise such dynamic representation engines use a concept of hidden class. Whenever an Object is created its hidden class is pointed to base, empty Object representation. Then each definition of new property makes a transition on hidden class graph, introducing hidden classes that are not yet defined, as in following example:

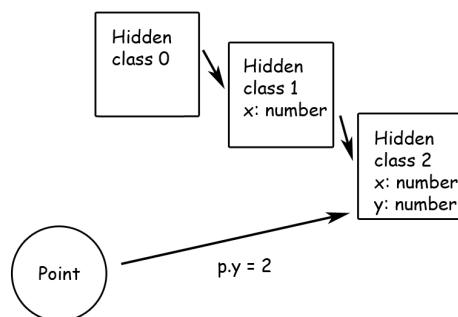
Rysunek 2.3: Initial shape of hidden class for Point



Rysunek 2.4: Shape of hidden class for Point after x property added

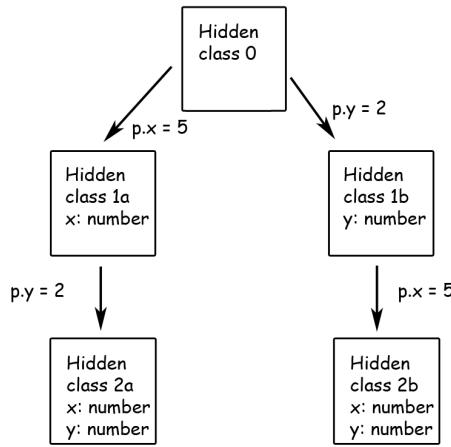


Rysunek 2.5: Shape of hidden class for Point after y property added



Based on hidden class further JIT compiler optimises methods, to generate even simpler assembly code similar to one compiled from C++. Class shape defines address offsets of Object properties. Thus, hidden class graph is actually a tree, where one class can't be reached in more than one way.

Rysunek 2.6: Two point representations based on order of declared properties



At the moment of writing type of property is not tracked in hidden classes. The only exception are primitive values (see Listing 2.2). In other words, storing an object in property results in the same hidden class regardless of hidden class of this object.

Transitions between hidden classes can be tracked in V8 using flags `-trace-generalization` tracking when variables are casted to more generic type (e.g. SMI to Integer, or Integer to Number) and `-trace-migration` (tracking when hidden classes are migrated).

```

1 // TODO: update when it lands in V8
2
3 [generalizing xQ] I:s->d (+20 maps) [xQ.Kd+919 at :719]
4 [generalizing xQ] Si:s->d (+3 maps) [xQ.Kd+1057 at :719]
5 [migrating xQ] I:s->d Si:s->d
6 [migrating xQ] I:s->d Si:s->d
  
```

Listing 2.3: Log of migration trace in V8

2.4. Garbage collection

Memory in JavaScript is managed automatically. Each allocation puts an object on memory heap. First generation of garbage collection traversed the whole tree and freed memory for all inaccessible objects. This type of deallocation is called mark-sweep and is causing taking a long time. Since JavaScript is single-threaded, this operation is blocking all other operations. To improve performance, especially in games, incremental scavange method of garbage collection was introduced. Engine tracks age of objects, allowing to quickly detect objects allocated temporarily (e.g. for a single frame rendered in game). When object is inaccessible, it's queued for deallocation, in chunks that don't cause long UI freezes.⁶⁷

TODO: check and extent

```

1 [1592]      34 ms: Scavenge 1.6 (18.8) -> 0.9 (18.8) MB, 0.0 ms [Runtime::PerformGC].
2 [1592]      37 ms: Scavenge 1.6 (18.8) -> 1.2 (19.8) MB, 1.0 ms [Runtime::PerformGC].
3 [1592]      40 ms: Scavenge 1.9 (19.8) -> 1.7 (19.8) MB, 1.0 ms [Runtime::PerformGC].
4 [1592]      43 ms: Scavenge 2.4 (19.8) -> 2.2 (19.8) MB, 2.0 ms [Runtime::PerformGC].
5 [1592]      49 ms: Scavenge 3.7 (19.8) -> 3.3 (20.8) MB, 3.0 ms [Runtime::PerformGC].
6 [1592]      56 ms: Scavenge 4.8 (20.8) -> 4.3 (21.8) MB, 3.0 ms [Runtime::PerformGC].
7 [1592]      74 ms: Scavenge 7.2 (21.8) -> 6.5 (23.8) MB, 6.0 ms [Runtime::PerformGC].
8 [1592]      98 ms: Scavenge 9.4 (23.8) -> 8.6 (24.8) MB, 5.0 ms [Runtime::PerformGC].
9 [1592]     194 ms: Scavenge 14.4 (24.8) -> 11.8 (25.8) MB, 23.0 ms [Runtime::PerformGC].
10 [1592]     340 ms: Scavenge 15.9 (25.8) -> 14.1 (30.8) MB, 15.0 ms
    (+ 10.0 ms in 41 steps since last GC) [Runtime::PerformGC].
11 [1592]     689 ms: Mark-sweep 18.7 (30.8) -> 14.0 (32.8) MB, 7.0 ms
12 [1592]     (+ 20.0 ms in 113 steps since start of marking, biggest step 1.0 ms)
13 [1592]           [StackGuard GC request] [GC in old space requested].
14 [1592]     1240 ms: Scavenge 21.8 (32.8) -> 14.0 (32.8) MB, 0.0 ms [Runtime::PerformGC].
15 [1592]     1799 ms: Scavenge 21.8 (32.8) -> 14.0 (32.8) MB, 0.0 ms [Runtime::PerformGC].
16 [1592]     2350 ms: Scavenge 21.8 (32.8) -> 14.0 (32.8) MB, 1.0 ms [Runtime::PerformGC].
17 [1592]     2902 ms: Scavenge 21.8 (32.8) -> 14.0 (32.8) MB, 1.0 ms [Runtime::PerformGC].
18 [1592]

```

Listing 2.4: Log of garbage collection in V8

⁶http://en.wikipedia.org/wiki/Cheney's_algorithm

⁷[http://en.wikipedia.org/wiki/Garbage_collection_\(computer_science\)](http://en.wikipedia.org/wiki/Garbage_collection_(computer_science))

3. Particle system

Particle system is one of most commonly used techniques to simulate smoke, fire, rain and other groups of discrete objects, usually independent from each other. System consist of defined number of emitters, producing lightweight particle objects with certain parameters. Each emitter has defined production ratio and each particle a certain lifespan, resulting in upper limit of total particles on screen. Some systems use also attraction points which enable better control over particles, using equations often similar to those of electrostatic forces. Such simulation is independent from rendering. The same particle system may be used for different effects with proper configuration.

Rysunek 3.1: Example rendering of tested particle system



3.1. System parameters

Tested system works on two-dimensional Cartesian plane. For purpose of performance analysis movements are calculated based only on frames rather than actual flow of time. This means that systems with different framerate will result in different visualisations, but requesting given amount of frames rendered will result in the same lifespan and total number of particles in both systems.

Emitter supports following parameters:

- position - initial position of created particles
- angle - angle counting clockwise from vector [0, 1]
- spread - parameter controlling random differences in initial angle of particles
- velocity - initial velocity of particles, in pixels per frame
- velocity spread - parameter controlling random differences in initial velocity of particles
- lifespan - initial lifespan of particles
- productionRate - amount of particles initialized in each frame

A Particle has similar properties:

- position
- velocity
- lifespan
- age - counted in frames, when higher then lifespan particle is removed from system

Source code of both implementations is attached in Appendix B.

3.2. Implementation with high memory allocation

Initial tested implementation has one very important property of particle emitter. Whenever new particles are created, new array of pointers is allocated and returned from emitter. System appends new particles to existing array. In each frame particle system creates new, empty array of particles and adds there only particles that are still alive. Array from previous frame and all dead particles are removed from system and deallocated. This is clearly suboptimal solution that allocates and deallocates plenty of memory in each frame. Purpose of this exercise is to show how both languages handle bad code and how big impact it has comparing to the optimal solution.

TODO: this part may need to be updated before publication. TODO: Is this accounting properly for v8 startup time? Maybe profiling ticks would be better.

```

1 $ time browser/static/d8 browser/static/particles1.js
2
3 real    0m20.619s
4 user    0m0.000s
5 sys     0m0.015s

```

Listing 3.1: Time measurement of unoptimized particle system in JavaScript

```

1 $ time runtime/static/particles1
2
3 real    0m2.606s
4 user    0m1.950s
5 sys     0m0.498s

```

Listing 3.2: Time measurement of unoptimized particle system in C++

Time measurement shows that JavaScript version is almost 8 times slower than native one. To analyse situation –prof and –log-timer-events flags may be used. Output file v8.log is parsed using available online tool.¹

```

1 Statistical profiling result from null, (28293 ticks, 2631 unaccounted, 0 excluded).
2
3 [Shared libraries]:
4   ticks  total  nonlib    name
5   9577   37.3%   0.0%  D:\Dropbox\praca_magisterska\physics\browser\static\d8.exe
6   1078    4.2%   0.0%  C:\Windows\SysWOW64\ntdll.dll
7     3    0.0%   0.0%  C:\Windows\syswow64\kernel32.dll
8     2    0.0%   0.0%  C:\Windows\syswow64\KERNELBASE.dll
9
10 [JavaScript]:
11   ticks  total  nonlib    name
12   4621   18.0%  30.8%  LazyCompile: ~verifyIfAlive :463
13   2228    8.7%  14.9%  LazyCompile: ~stepParticle :460
14   1800    7.0%  12.0%  LazyCompile: ~smash.ParticleSystem.step :449
15   1018    4.0%   6.8%  Stub: CompareICStub

```

¹http://v8.googlecode.com/svn/branches/bleeding_edge/tools/profviz/profviz.html

```

16    949   3.7%   6.3%  Stub: LoadFieldStub {1}
17    831   3.2%   5.5%  LazyCompile: ~<anonymous> :466
18    799   3.1%   5.3%  Builtin: A builtin from the snapshot
19    770   3.0%   5.1%  Stub: CompareICStub {1}
20    739   2.9%   4.9%  Stub: CallFunctionStub
21    614   2.4%   4.1%  LazyCompile: IN native runtime.js:348
22    549   2.1%   3.7%  Stub: LoadFieldStub
23    430   1.7%   2.9%  Stub: CEntryStub
24    259   1.0%   1.7%  LazyCompile: *forEach native array.js:1188
25    246   1.0%   1.6%  LazyCompile: *verifyIfAlive :463
26    169   0.7%   1.1%  LazyCompile: *stepParticle :460
27    145   0.6%   1.0%  LazyCompile: *<anonymous> :466
28    129   0.5%   0.9%  Stub: LoadFieldStub {3}
29    127   0.5%   0.8%  LazyCompile: *smash.ParticleEmitter.getNewParticles :429
30    121   0.5%   0.8%  Stub: CompareICStub {2}
31     86   0.3%   0.6%  Stub: TranscendentalCacheStub {1}
32     79   0.3%   0.5%  Stub: ParticleSystem {1}
33     79   0.3%   0.5%  Stub: LoadFieldStub {4}
34     78   0.3%   0.5%  Stub: LoadFieldStub {2}
35     65   0.3%   0.4%  Stub: TranscendentalCacheStub
36     52   0.2%   0.3%  Stub: RecordWriteStub
37     42   0.2%   0.3%  Stub: CallFunctionStub_Args1
38     34   0.1%   0.2%  Stub: LoadFieldStub {5}
39     30   0.1%   0.2%  Stub: InterruptStub
40     14   0.1%   0.1%  LazyCompile: ~appendNewParticles :455
41      8   0.0%   0.1%  Stub: KeyedLoadElementStub
42      5   0.0%   0.0%  LazyCompile: ~forEach native array.js:1188
43      5   0.0%   0.0%  LazyCompile: *appendNewParticles :455
44      3   0.0%   0.0%  LazyCompile: *smash.Particle :389
45      3   0.0%   0.0%  Builtin: A builtin from the snapshot {1}
46      2   0.0%   0.0%  Stub: CEntryStub {1}
47      2   0.0%   0.0%  LazyCompile: ~smash.ParticleEmitter.getNewParticles :429
48      1   0.0%   0.0%  Stub: ToBooleanStub
49      1   0.0%   0.0%  Stub: FastNewClosureStub
50      1   0.0%   0.0%  Stub: CompareICStub {3}
51      1   0.0%   0.0%  Stub: CallConstructStub
52      1   0.0%   0.0%  Stub: BinaryOpStub_ADD_OverwriteRight_Smi+Number
53      1   0.0%   0.0%  LazyCompile: APPLY_PREPARE native runtime.js:432
54      1   0.0%   0.0%  LazyCompile: *random native math.js:188
55      1   0.0%   0.0%  KeyedLoadIC: {55}
56      1   0.0%   0.0%  Function: ~stepParticle :460
57
58 [C++]:
59   ticks  total  nonlib   name
60
61 [GC]:
62   ticks  total  nonlib   name
63   2067   8.1%

```

Listing 3.3: Profiler output for unoptimized particles

Methods prefixed with `~` are unoptimized, the ones prefixed with `*` are JIT compiled. As seen in profiler log, most of the time is spent in unoptimised versions of `verifyIfAlive` and `stepParticle` methods of particle system step.

```

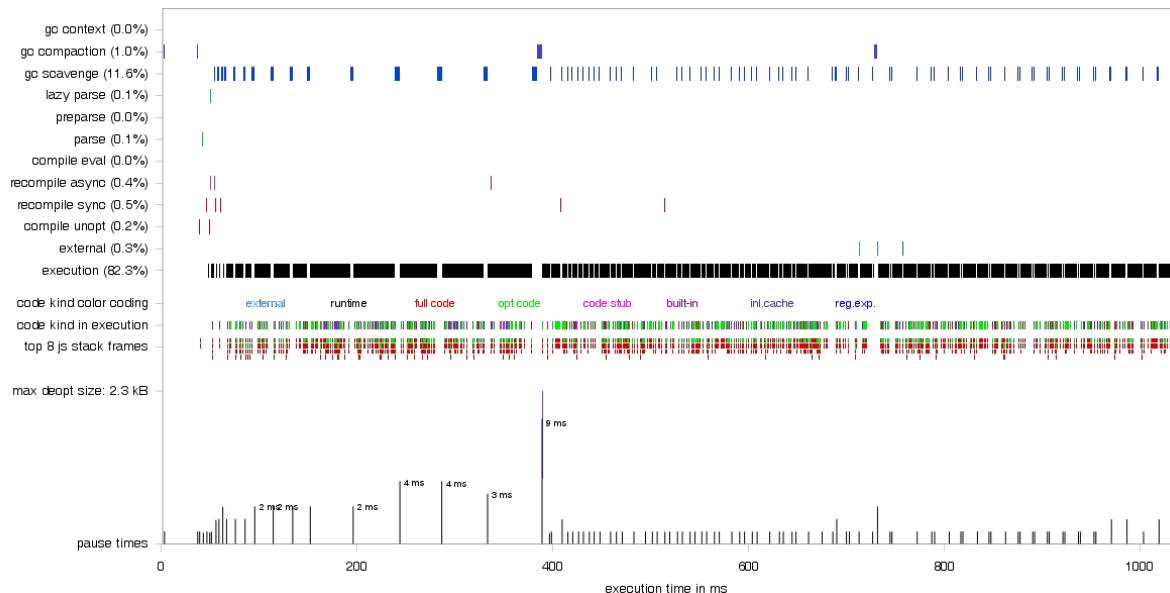
1 smash.ParticleSystem.prototype.step = function() {
2   this.emitters.forEach(function appendNewParticles(a) {
3     this.particles.push.apply(this.particles, a.getNewParticles())
4   }, this);
5   var newParticles = [];
6   function stepParticle(a) {
7     a.step();
8   }
9   function verifyIfAlive(a) {
10     if (0 <= a.positionX && a.positionX < smash.ParticleSystem.CANVAS_WIDTH &&
11         0 <= a.positionY && a.positionY < smash.ParticleSystem.CANVAS_HEIGHT &&
12         a.age < a.lifespan) {
13       newParticles.push(a);
14     }
15   }
16   this.particles.forEach(function (a) {
17     stepParticle(a);
18     verifyIfAlive(a);
19   }, this);
20   this.particles = newParticles;
21 };

```

Listing 3.4: Annotated part of source

The same methods are also used in optimised versions, where they take significantly less ticks to run. It's clear that presented code not only allocates and deallocates too much memory, but also fails to run in optimised mode. It's visible on chart obtained from the same tool - stripe labelled code kind in execution shows multiple kinds of code running and is interrupted often with garbage collection cycles.

Rysunek 3.2: Chart of time used in unoptimised verion of JavaScript



Garbage collection cycles blocking execution are also visible with `--trace-gc` flag.

```
1 $ browser/static/d8 --trace-gc browser/static/particles1.js
```

```

2 [9696]      10 ms: Scavenge 1.6 (18.8) -> 0.9 (18.8) MB, 0.0 ms [Runtime::PerformGC].
3 [9696]      14 ms: Scavenge 1.6 (18.8) -> 1.3 (19.8) MB, 2.0 ms [Runtime::PerformGC].
4 (...).
5 [9696]      233 ms: Scavenge 15.0 (25.8) -> 9.7 (25.8) MB, 4.0 ms [Runtime::PerformGC].
6 [9696]      277 ms: Scavenge 15.6 (26.8) -> 10.0 (27.8) MB, 4.0 ms
7      (+ 13.0 ms in 22 steps since last GC) [Runtime::PerformGC].
8 [9696] Limited new space size due to high promotion rate: 1 MB
9 [9696]      284 ms: Mark-sweep 10.6 (27.8) -> 10.4 (28.8) MB, 6.0 ms
10     (+ 14.0 ms in 23 steps since start of marking, biggest step 1.0 ms)
11     [StackGuard GC request] [GC in old space requested].
12 [9696]      294 ms: Scavenge 11.5 (28.8) -> 11.0 (29.8) MB, 1.0 ms [Runtime::PerformGC].
13 [9696]      295 ms: Scavenge 11.9 (29.8) -> 11.6 (30.8) MB, 0.0 ms [Runtime::PerformGC].
14 (...).
15 [9696]      555 ms: Scavenge 43.4 (68.8) -> 43.4 (69.8) MB, 1.0 ms [Runtime::PerformGC].
16 [9696] Increasing marking speed to 3 due to high promotion rate
17 [9696]      564 ms: Scavenge 43.9 (69.8) -> 43.6 (69.8) MB, 1.0 ms
18      (+ 4.0 ms in 3 steps since last GC) [Runtime::PerformGC].
19 [9696]      576 ms: Scavenge 44.2 (69.8) -> 44.2 (70.8) MB, 1.0 ms
20      (+ 8.0 ms in 2 steps since last GC) [Runtime::PerformGC].
21 [9696]      581 ms: Mark-sweep 44.9 (70.8) -> 13.4 (61.8) MB, 3.0 ms
22      (+ 14.0 ms in 6 steps since start of marking, biggest step 2.0 ms)
23     [StackGuard GC request] [GC in old space requested].
24 [9696]      591 ms: Scavenge 14.3 (61.8) -> 14.1 (61.8) MB, 0.0 ms [Runtime::PerformGC].
25 (...).
```

Listing 3.5: Garbage collection in unoptimised particle system

3.3. Implementation with object pool

To improve performance different approach to particles allocation is used. Each particle has a flag "isDead" telling if it may be safely reused for new particle. Particle pool is kept along with a list of pointers to dead particles. This way when system reaches it's maximum congestion (around 15000 particles in given example) no new allocations occur. Creation of new particles is moved from particle emitter to particle system, to avoid allocation of new array. Emitter works now as a structure describing behaviour but not implementing one.

```

1 $ time browser/static/d8 browser/static/particles2.js
2
3 real    0m3.275s
4 user    0m0.000s
5 sys     0m0.015s

```

Listing 3.6: Time measurement of optimized particle system in JavaScript

```

1 $ time runtime/static/particles2
2
3 real    0m1.483s
4 user    0m1.387s
5 sys     0m0.000s

```

Listing 3.7: Time measurement of optimized particle system in C++

Optimised version shows overall improvement of 85% for JavaScript and 45% for C++ making JavaScript version only 2.2 times slower than native one. It's clearly visible that JavaScript is more sensitive to unwise memory management.

```

1 Statistical profiling result from null, (3780 ticks, 2 unaccounted, 0 excluded).
2
3 [Shared libraries]:
4   ticks  total  nonlib  name
5     98    2.6%   0.0%  D:\Dropbox\praca_magisterska\physics\browser\static\d8.exe
6      6    0.2%   0.0%  C:\Windows\SysWOW64\ntdll.dll
7
8 [JavaScript]:
9   ticks  total  nonlib  name
10    3476   92.0%  94.6%  LazyCompile: *f.step browser/static/particles2.js:28
11     101    2.7%   2.7%  Stub: TranscendentalCacheStub {1}
12      89    2.4%   2.4%  Stub: TranscendentalCacheStub
13       5    0.1%   0.1%  Script: ~browser/static/particles2.js
14       1    0.0%   0.0%  Stub: TranscendentalCacheStub {2}
15       1    0.0%   0.0%  Stub: BinaryOpStub_MUL_OverwriteLeft_Number+Number
16       1    0.0%   0.0%  LazyCompile: *sin native math.js:199
17       1    0.0%   0.0%  Builtin: A builtin from the snapshot
18
19 [C++]:
20   ticks  total  nonlib  name
21

```

```

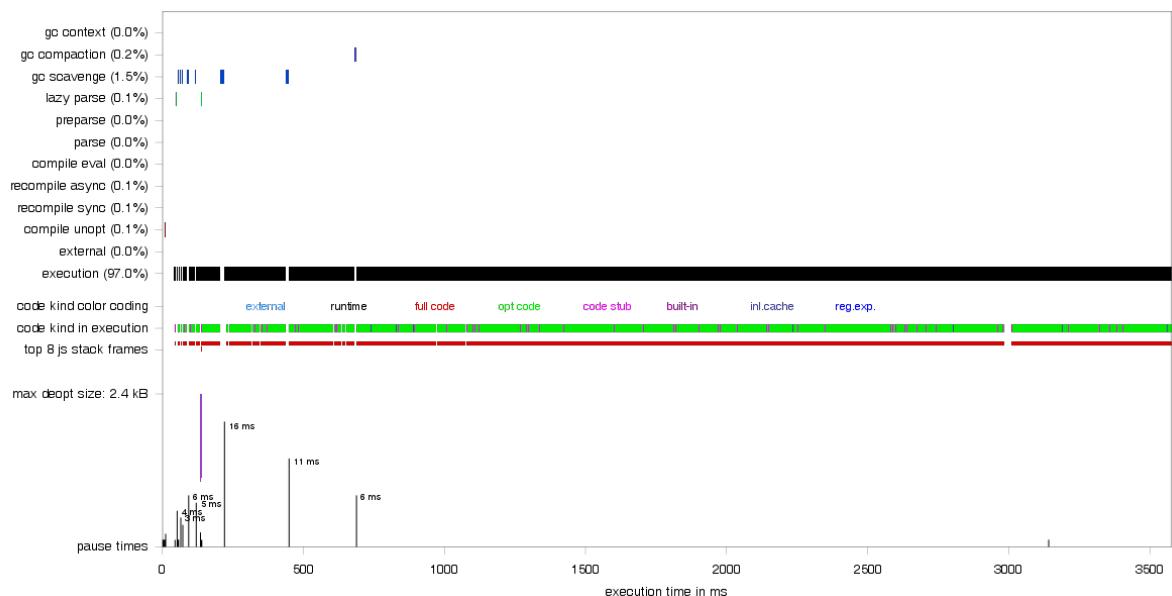
22 [GC]:
23   ticks  total  nonlib   name
24      59    1.6%

```

Listing 3.8: Profiler output for optimized particles

Profiling shows that step method of particle system now runs always in optimised mode and almost no time is spent on other methods. The same is visible on profiling chart, where code kind in execution stripe shows only optimised code.

Rysunek 3.3: Chart of time used in optimised verion of JavaScript



Situation is also improved in garbage collection log.

```

1 $ browser/static/d8 --trace-gc browser/static/particles2.js
2 [8348]      10 ms: Scavenge 1.6 (18.8) -> 0.9 (18.8) MB, 1.0 ms [Runtime::PerformGC].
3 [8348]      13 ms: Scavenge 1.6 (18.8) -> 1.2 (19.8) MB, 1.0 ms [Runtime::PerformGC].
4 [8348]      16 ms: Scavenge 1.9 (19.8) -> 1.7 (19.8) MB, 1.0 ms [Runtime::PerformGC].
5 [8348]      19 ms: Scavenge 2.4 (19.8) -> 2.2 (19.8) MB, 2.0 ms [Runtime::PerformGC].
6 [8348]      25 ms: Scavenge 3.7 (19.8) -> 3.3 (20.8) MB, 3.0 ms [Runtime::PerformGC].
7 [8348]      32 ms: Scavenge 4.8 (20.8) -> 4.3 (21.8) MB, 2.0 ms [Runtime::PerformGC].
8 [8348]      50 ms: Scavenge 7.2 (21.8) -> 6.5 (23.8) MB, 5.0 ms [Runtime::PerformGC].
9 [8348]      75 ms: Scavenge 9.4 (23.8) -> 8.6 (24.8) MB, 5.0 ms [Runtime::PerformGC].
10 [8348]     173 ms: Scavenge 14.4 (24.8) -> 11.8 (25.8) MB, 24.0 ms [Runtime::PerformGC].
11 [8348]     319 ms: Scavenge 15.9 (25.8) -> 14.1 (30.8) MB, 15.0 ms
12     (+ 9.0 ms in 44 steps since last GC) [Runtime::PerformGC].
13 [8348]     669 ms: Mark-sweep 18.7 (30.8) -> 14.0 (32.8) MB, 7.0 ms
14     (+ 17.0 ms in 116 steps since start of marking, biggest step 1.0 ms)
15     [StackGuard GC request] [GC in old space requested].
16 [8348]     1229 ms: Scavenge 21.8 (32.8) -> 14.0 (32.8) MB, 0.0 ms [Runtime::PerformGC].
17 [8348]     1793 ms: Scavenge 21.8 (32.8) -> 14.0 (32.8) MB, 0.0 ms [Runtime::PerformGC].
18 [8348]     2353 ms: Scavenge 21.8 (32.8) -> 14.0 (32.8) MB, 0.0 ms [Runtime::PerformGC].
19 [8348]     2914 ms: Scavenge 21.8 (32.8) -> 14.0 (32.8) MB, 1.0 ms [Runtime::PerformGC].

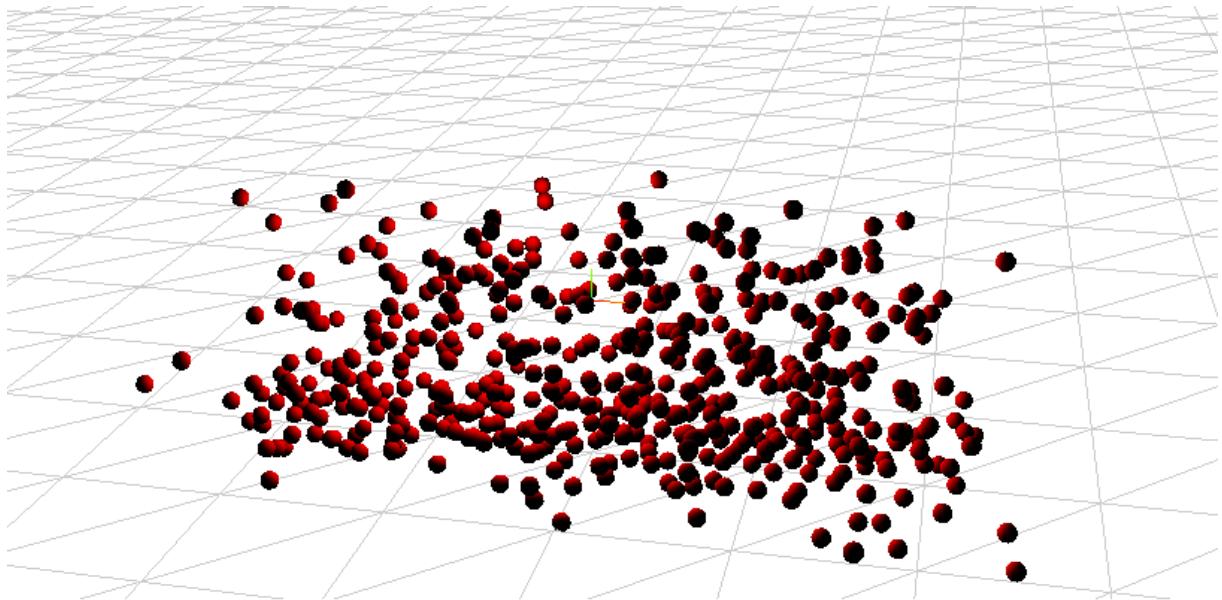
```

Listing 3.9: Garbage collection in optimised particle system

4. Sphere collision

Spheres are the simplest of bounding shapes used in collision detection. This chapter presents tests for two versions of algorithms - naive $O(N^2)$ approach and with partitioned space. While simpler algorithm has far greater number of collision checks per frame, it allocates almost no memory per frame. More complex method will minimise number of checks, but additional structure and steps added may influence overall execution time in unexpected way.

Rysunek 4.1: Example rendering of tested sphere collision system



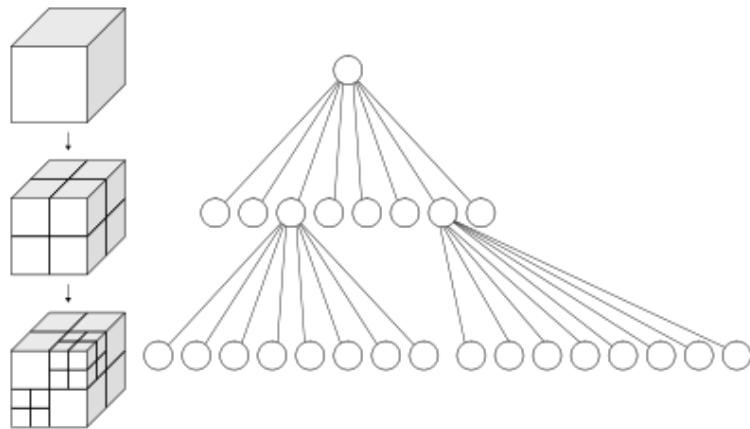
4.1. Algorithm description

Collision detection for spheres is a trivial task. If distance between two spheres is smaller than sum of their radiiuses, spheres collide.

$$\sqrt{(S_1.x - S_2.x)^2 + (S_1.y - S_2.y)^2 + (S_1.z - S_2.z)^2} < S_1.radius + S_2.radius$$

While the equation is simple, with large number N of colliding objects complexity of this detection is $O(N^2)$. Methods of space partitioning are used to reduce number of checks. One used in this benchmark is Octree. Base for algorithm is a tree-like structure of bounding boxes. Whenever a box contains more than one colliding object, it's divided into eight smaller boxes, by partitioning each edge by 2. When maximum tree depth is reached, multiple objects are stored in one box. One object may be referenced from multiple boxes, when its size and position make them intersect. Each movement requires a check if object has already moved to one of neighbour boxes.

Rysunek 4.2: Octree structure. Source: <http://en.wikipedia.org/wiki/File:Octree2.svg/>



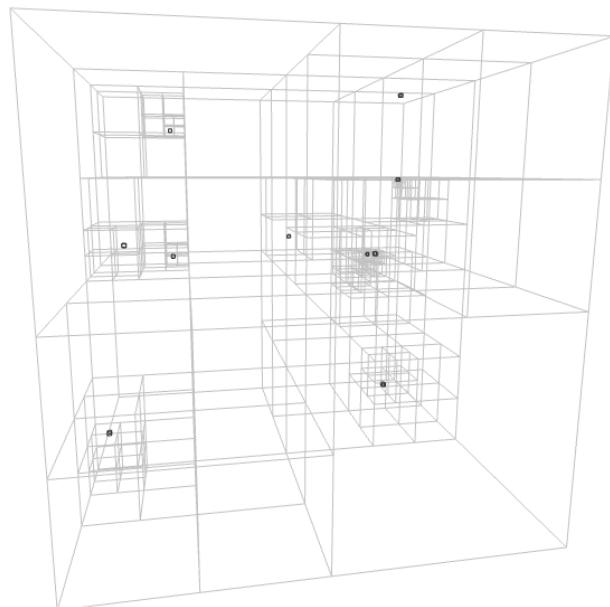
Having objects grouped in boxes reduces complexity of collision check. Since an object may collide only with objects in the same box, number of checks is much smaller. Overall complexity of Octree checks is $O(N \log N)$. TODO: reference for complexity.

When collision is detected, collision response is calculated. Its result is directly derived from rule of conservation of momentum and conservation of kinetic energy.

$$\begin{aligned} m_1 * \vec{v}_1 + m_2 * \vec{v}_2 &= m_1 * \vec{v}'_1 + m_2 * \vec{v}'_2 \\ \frac{m_1}{2} * \vec{v}_1^2 + \frac{m_2}{2} * \vec{v}_2^2 &= \frac{m_1}{2} * \vec{v}'_1^2 + \frac{m_2}{2} * \vec{v}'_2^2 \end{aligned}$$

TODO: add math here, finish this chapter.

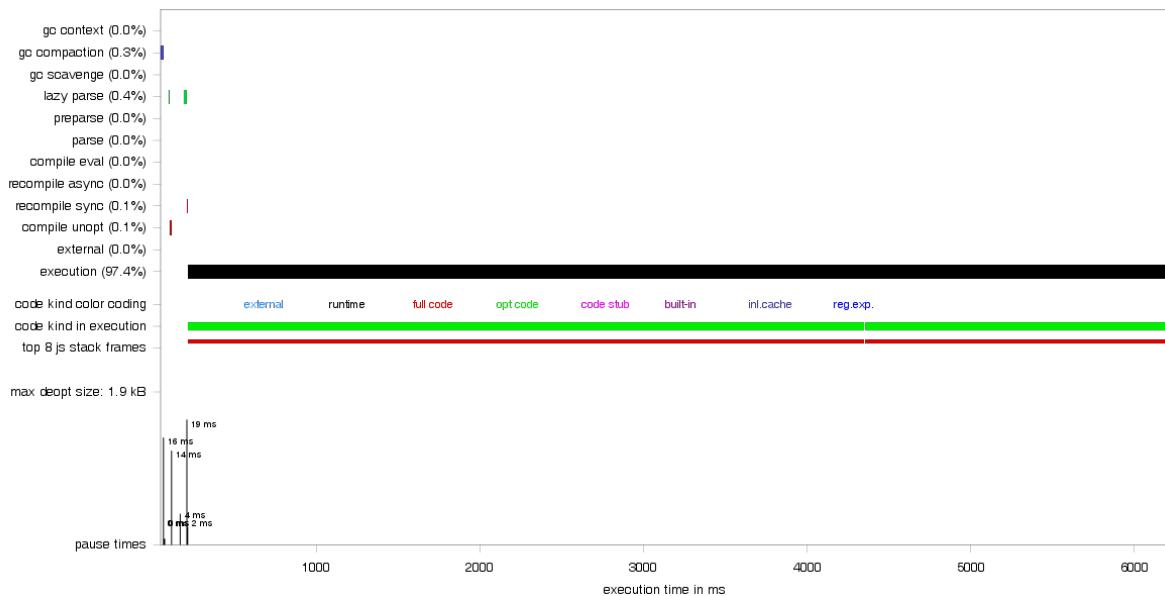
Rysunek 4.3: Example of WebGL Octree debug rendering. Available online at <http://pawlowski.it/octtree/>



4.2. $O(N^2)$ approach

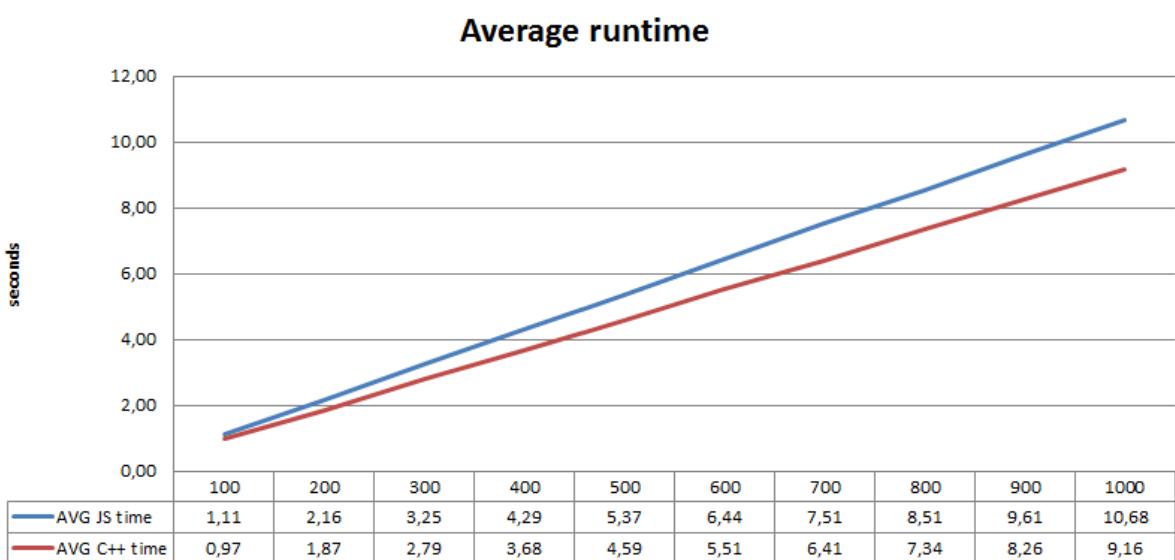
Naive approach for collision detection proves to be easy to implement in JavaScript. Since almost no memory is allocated in each frame, no garbage collection issues appear. All methods are well defined and work mostly on floats. This results in highly optimised binary code produced by compiler, as shown on 4.4.

Rysunek 4.4: Chart of time used in optimised version of JavaScript

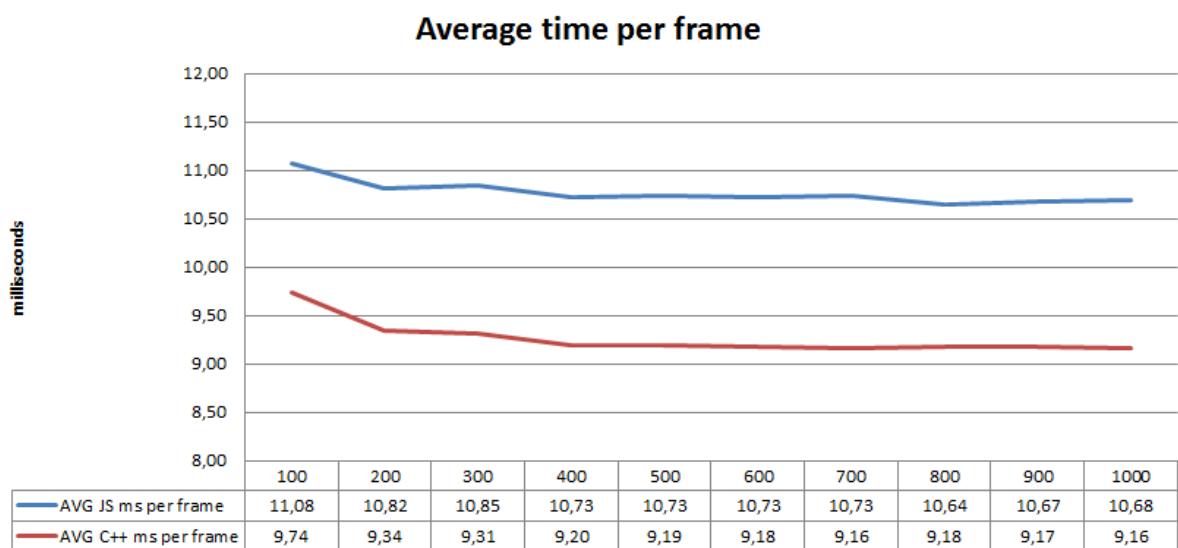


Multiple tests with $N=1000$ and different number of frames rendered show, that for simple mathematical task performance of JavaScript is very close to this of C++. On average, JavaScript version of benchmark runs 15% longer than C++ one.

Rysunek 4.5: Comparison of total execution time. $N = 1000$, varying number of frames.

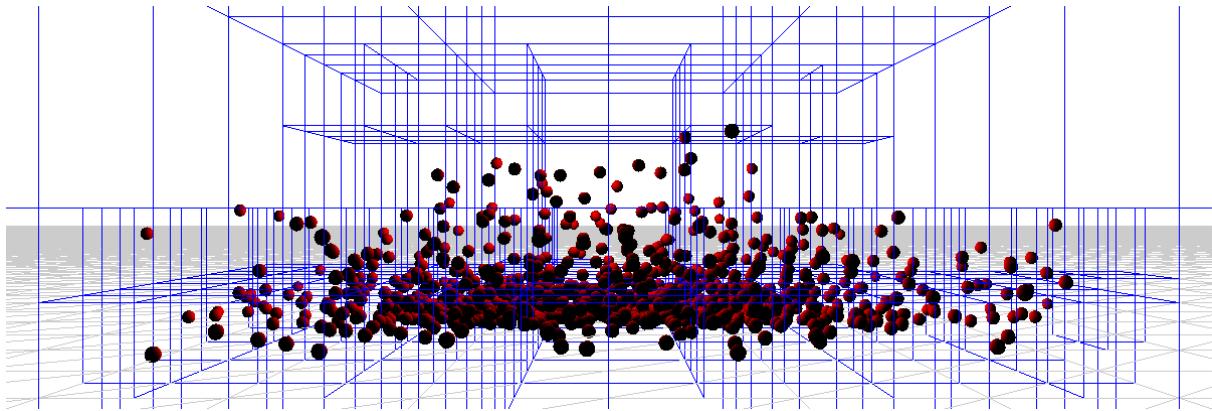


Rysunek 4.6: Comparison of execution time per frame. $N = 1000$, varying number of frames.



4.3. Octree-partitioned space

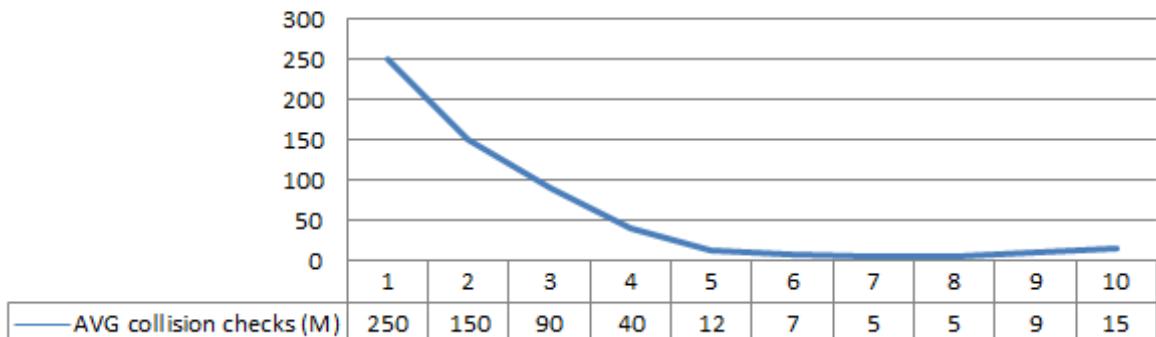
Rysunek 4.7: Octree partitioned sphere collision system



Tests with Octree partitioning were executed with $N=1000$ spheres and $T=1000$ frames. Varying value is maximum depth of Octree, ranging from 1 to 10. Changing maximum depth reduces number of collision checks between spheres, as shown on 4.8.

Rysunek 4.8: Number of collisions in Octree

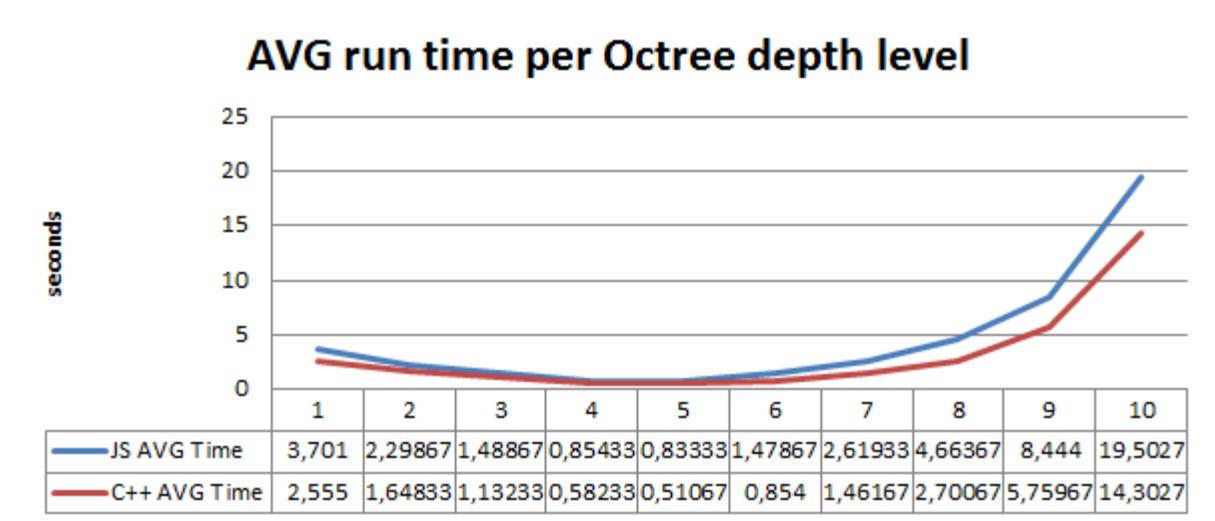
AVG collision checks (millions) per Octree level



For low values overall complexity of checks doesn't change significantly, since most of spheres are in one or few bounding cubes and no checks are skipped. Additional operations related to Octree are actually making this solution slower than $O(n^2)$ approach. For depth values in optimal zone, number of collision is reduced by factor of at least 10, while keeping Octree overhead reasonable. Interesting thing happens when maximum level of Octree is very high and edge of smallest Octree cube approaches size of spheres. Number of transitions between partitioning cubes, related memory allocation and cleanups actually make this approach much slower, as shown on 4.9. Moreover, some spheres are references in more than one cube, raising again number of collision checks.

It's clearly visible that number of collision checks and run time is correlated only up to certain point. For deep Octrees number of checks doesn't improve further, but overall run time is getting longer. Performance of JavaScript in relation to C++ varies between 30% to 80% overhead. In comparison with $O(n^2)$ approach, optimal Octree in JavaScript runs over 92% faster and C++ over 94% faster.

Rysunek 4.9: Run times in Octree system

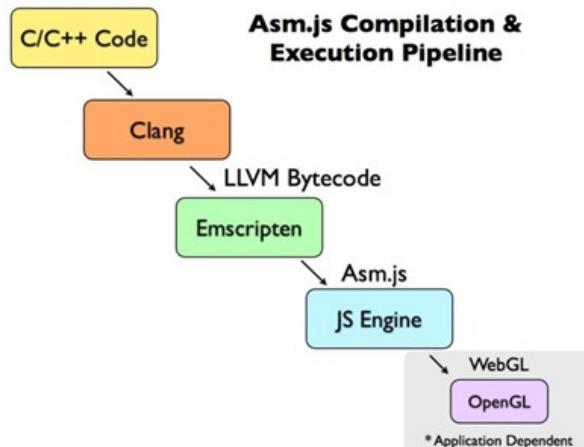


5. Emscripten

JavaScript is often called an assembly language of the Web.¹ One could argue that since only one language is supported by browsers it could be made a compilation target similar to assembler for CPU. This statement is flawed since eventually JavaScript is translated to assembly making it only an intermediate step. Probably resemblance to ByteCode in JVM, which is compilation target of multiple languages like Java, Scala and Clojure is more in place. Nevertheless, last years showed multiple projects aimed at converting code to JavaScript. Some introduce new syntax like CoffeeScript, Dart or TypeScript while still serving the same purpose - providing human readable code that is interpreted in browser on fly. Others, that are focus of this chapter, aim to convert existing projects to run in browser.

Several new projects are connected to make this happen. First steps in conversion between languages were made with LLVM project² which currently is a collection of tools and compilers converting code to and from intermediate representation (LLVM IR). For C++ Clang³ is a conversion tool.

Rysunek 5.1: Pipeline of Emscripten conversion. Source:
<http://www.hanselman.com/blog/JavaScriptIsWebAssemblyLanguageAndThatsOK.aspx>



Code in LLVM is suitable for further conversion to language like JavaScript. This part is handled by Emscripten⁴ project. Initially compilation target for Emscripten was plain JavaScript. With recent developments asm.js⁵ library was created. It provides syntax built on top of JavaScript, that is strongly typed and easily translatable to assembly language. Asm.js details are explained in section 5.1.

¹<http://www.hanselman.com/blog/JavaScriptIsWebAssemblyLanguageAndThatsOK.aspx>

²<http://llvm.org/>

³<http://clang.llvm.org/>

⁴<https://github.com/kripken/emscripten/wiki>

⁵<http://asmjs.org/spec/latest/>

```

1 do {
2   if (a[k + 22 | 0] << 24 >> 24 == 30) {
3     h = b[k + 14 >> 1] | 0;
4     if ((h - 1 & 65535) > 1) {
5       break
6     }
7     l = c[j >> 2] | 0;
8     p = (c[1384465] | 0) + 3 | 0;
9     if (p >>> 0 < 26) {
10       s = (2293760 >>> (p >>> 0) & 1 | 0) != 0 ? 0 : -1e3
11     } else {
12       s = -1e3
13     }
14     if (!(Vq(d, l, k | 0, h << 16 >> 16, s) | 0)) {
15       break
16     }
17     g[(c[f >> 2] | 0) + (l * 112 & -1) + 56 >> 2] = +(b[k + 12 >> 1] << 16 >> 16 | 0);
18     h = (c[f >> 2] | 0) + (l * 112 & -1) + 60 | 0;
19     l = k + 28 | 0;
20     c[h >> 2] = c[l >> 2] | 0;
21     c[h + 4 >> 2] = c[l + 4 >> 2] | 0;
22     c[h + 8 >> 2] = c[l + 8 >> 2] | 0;
23     c[h + 12 >> 2] = c[l + 12 >> 2] | 0;
24     c[h + 16 >> 2] = c[l + 16 >> 2] | 0;
25     c[h + 20 >> 2] = c[l + 20 >> 2] | 0;
26     c[h + 24 >> 2] = c[l + 24 >> 2] | 0
27   }
28 } while (0);

```

Listing 5.1: Example of code using asm.js

Project, built in cooperation with Mozilla Foundation, has its own engine for Firefox - OdinMonkey, designed to run faster for this limited and well-defined syntax.

Altogether these projects resulted in multiple libraries and games converted from native version to JavaScript.

Proof-of-concept demo made in cooperation between Mozilla and Unreal is Epic Citadel HTML5 - Unreal Engine 3 technology demo⁶ instance running in browser.⁷ Companies claim it took only four days to complete the conversion.

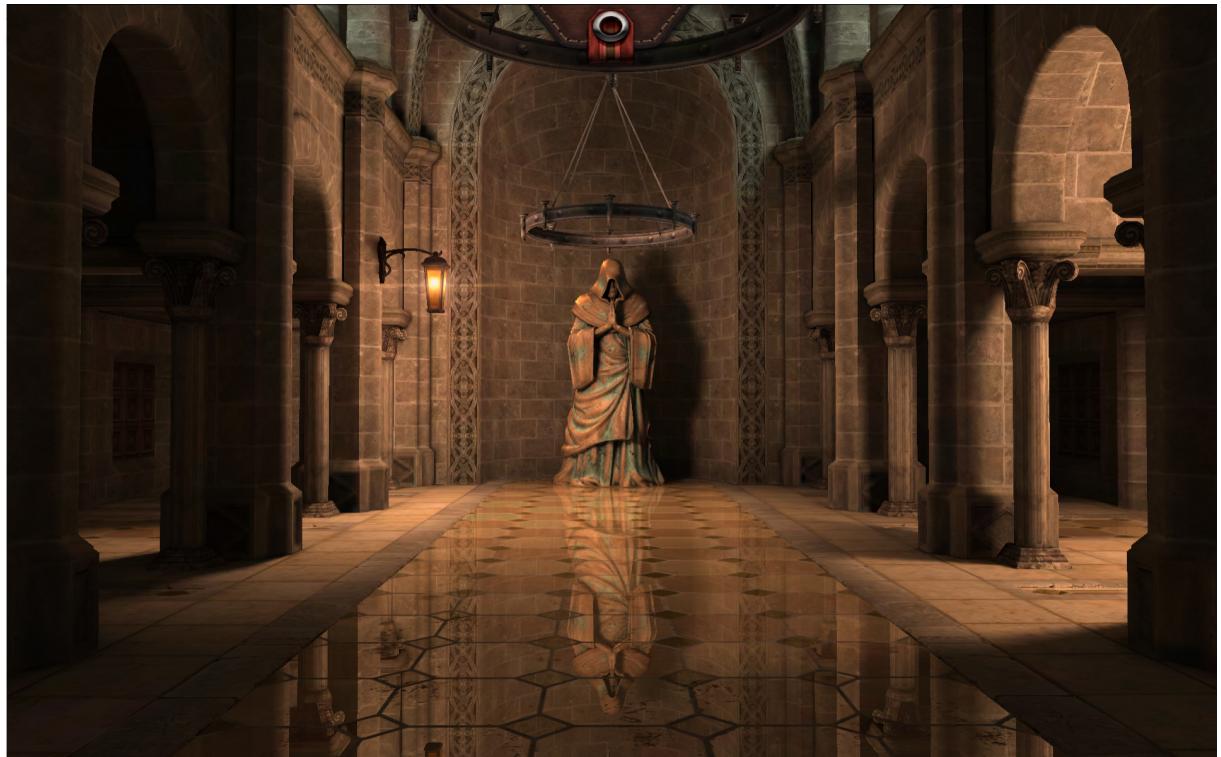
Another example of successful converted project is ammo.js⁸ - originating from Bullet physics engine. TODO: Maybe extend this part a bit, cover more on how conversion was going and what were the issues.

⁶http://www.unrealengine.com/en/showcase/udk/epic_citadel/

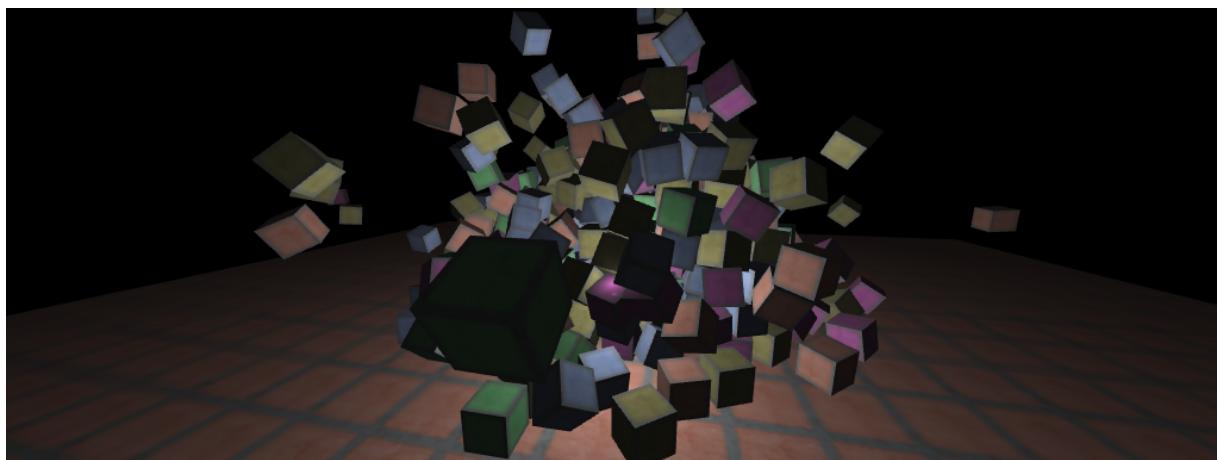
⁷<http://www.unrealengine.com/html5/>

⁸<https://github.com/kripken/ammo.js/>

Rysunek 5.2: Epic Citadel screenshot



Rysunek 5.3: Ammo.js demo colliding 500 boxes at 30fps, available at
<http://kripken.github.io/ammo.js/examples/new/ammo.html>



5.1. Asm.js overview

Asm.js introduces some improvements targeted to fix performance problems of JavaScript. Ahead of time compilation enforces very specific rules on coding style. Documentation⁹ lists:

5.1.1. Unboxed representations of integers and floating-point numbers

In asm.js only types allowed are integers and doubles. All numbers have annotations indicating static type (see: 2.2). This way compiler doesn't have to detect possible transitions between variable types and code overall runs faster.

5.1.2. Absence of runtime type checks

Since asm.js works only on well-defined numbers, all function calls are monomorphic and stable. In OdinMonkey ahead-of-time compilation is able to compile them to the most optimised version without tracking method calls. In engines using JIT methods are compiled early and newer deoptimised.

5.1.3. Absence of garbage collection

As shown in previous chapters, garbage collection calls are often a performance bottleneck. Asm.js solves this problem by eliminating garbage collection completely. Memory is stored in short-life variables, deallocated after method exits and in global heaps, which are never resized or deallocated.

5.1.4. Efficient heap loads and stores

Heaps are global arrays of statically typed arrays, in JavaScript implemented as objects listed in 5.1. Size of heap doesn't change during runtime - it has to be calculated during compilation and incorrect prediction or memory leaks may result in buffer overflow. Heaps are always passed as an argument to asm.js modules. Each module may reference part of the heap and use it as long as necessary.

5.1.5. Summary

These solutions remove some of performance bottlenecks described in previous chapters. Code suitable to run with asm.js is almost unreadable by programmer and resembles assembly code. Asm.js is not designed to be a language used by a programmer, it is mainly a target for compilation using converters like Emscripten.

Most of optimisation used by asm.js are consistent with code that is expected by V8 engine - variables and methods are monomorphic, garbage collection is close to zero. It's worth noting that code written by hand is almost always shorter than one generated by Emscripten. Partial solution for this is built-in Google Closure Compiler used on output of Emscripten and different levels of optimisation. In tests mentioned in this work all

⁹<http://asmjs.org/spec/latest/>

Tablica 5.1: Statically typed arrays in JavaScript

View Type	Element Size (Bytes)	Element Type
Uint8Array	1	intish
Int8Array	1	intish
Uint16Array	2	intish
Int16Array	2	intish
Uint32Array	4	intish
Int32Array	4	intish
Float32Array	4	doublish
Float64Array	8	doublish

solutions take 2 to 4kB compiled, while Emscripten produces over 450kB of code for each. This affects real life performance by lengthening at least transfer and parse time for code. Average parse time of 1kB of JS is believed to be up to 1ms¹⁰. Global average bandwidth was 3.1 Mbps in Q1 2013¹¹ thus transfer of each kilobyte is around 2.5ms. In total, load time of tested code is approximately 1.5 second on average bandwidth and platform. In case of larger applications and games waiting time for load may be significantly larger and should be taken under consideration.

¹⁰<https://developers.google.com/speed/docs/best-practices/mobile>

¹¹http://www.akamai.com/dl/akamai/akamai_soti_q113.pdf

5.2. Benchmarks

All four test were compiled and run times were measured on different platforms.

Unoptimised version of particle system (see: 3.2) were designed to perform a lot of memory operations. In tests it's visible that C++ handles this task best. Code generated using Emscripten benefits from static memory heap which effectively works similar to object pool introduced later and runs approximately twice as long as C++. Plain JavaScript suffers greatly from memory allocation issues and unoptimised code, resulting in 6 times slower execution than C++.

Optimised particles (see: 3.3) with object pool and low garbage collection show how improvements of algorithm result in much faster JavaScript execution. It still takes twice as long to run particle system in V8, but Emscripten version takes three times longer than C++. Additional overhead of long and complex code is clearly visible and since JS code employs the same techniques that Emscripten uses automatically, there is no improvement in related areas. It's worth mentioning that unoptimised version of C++ particle system is slightly slower than optimised JavaScript one, showing that code quality improvement that doesn't affect algorithmic complexity of algorithm may be more important than choice of environment.

Tablica 5.2: Particle tests on different platforms

Platform	Unoptimised particles			Optimised particles		
	C++	JavaScript	Emscripten	C++	JavaScript	Emscripten
Fedora 19, Intel i7 2670QM, 4GB RAM, g++ 4.8.1	3.21s	19.51s	4.85s	1.63s	4.96s	5.10s
Windows 7, Intel i7 2670QM, 4GB RAM, g++ 4.7.3, Cygwin	3.51s	20.77s	6.46s	1.71s	3.47s	5.57s

Sphere collision test is putting high load on CPU.

In $O(n^2)$ version (see: 4.2) exactly 1 000 000 000 checks for object collisions are made. Overall execution time is surprisingly good for JavaScript with overhead of approximately 15% and 25% for Emscripten generated version. It's a result of putting focus on pure mathematical operations that are quickly compiled by V8 and processed on unboxed numbers in asm.js.

Space partitioning using Octree greatly reduces number of collisions (to less than 100 000) and execution time. To give meaningful results simulation time is increased from 1000 frames to 10000. Under these circumstances difference in run time changes to 20% for Javascript and stays similarly around 25% for Emscripten. This is result of small memory operations related to Octree areas.

Above results show how well written JavaScript or properly converted C++ are able to perform in browser with similar performance as native programs, rarely exceeding 100% overhead and sometimes getting as close as 15% to C++ execution time.

Tablica 5.3: Spheres tests on different platforms

Platform	$O(n^2)$ spheres			Octree spheres		
	C++	JavaScript	Emscripten	C++	JavaScript	Emscripten
Fedora 19, Intel i7 2670QM, 4GB RAM, g++ 4.8.1	4.96s	9.02s	12.35s	3.44s	14.14s	11.20s
Windows 7, Intel i7 2670QM, 4GB RAM, g++ 4.7.3, Cygwin	9.52s	10.81s	11.82s	14.10s	16.95s	17.79s

6. Summary

Conducted experiments show a gap between JavaScript and C++ performance. Significant language design differences result in code that is often easier to write but also easier to abuse. Benchmarks show differences between 15% and 100% overhead for correctly designed JavaScript code and over 500% for incorrect patterns. Considering Moore's law stating that computers double speed every 18 months it safe to say that JavaScript is very close to being suitable for any type of development. Recent projects varying from server side solutions¹² to hardware developer boards³ are proving it. From the perspective of game development, it is unlikely at the time of writing that AAA game may be created to run in browser. However, growing segments of casual, independent and social games are already targeting web as a platform.

Rysunek 6.1: Game created with ImpactJS



Multiple open-source and commercial game engines are created lately. Examples worth mentioning are ImpactJS⁴, Turbulenz⁵ and Isogenic Engine⁶.

Very important and growing sector are interactive 3D arts with two major targets - music videos and commercials. They are uniquely available only in browsers as a very viral extensions of normal marketing. On

¹<http://nodejs.org/>

²<http://googlecreativelab.github.io/coder/>

³<http://www.espruino.com/>

⁴<http://impactjs.com/>

⁵<http://biz.turbulenz.com/turbulenz>

⁶<http://www.isogenicengine.com/>

Rysunek 6.2: Game created with Isogenic Engine



of first occurrences of this use of technology was video for Rome group: "3 dreams of black"⁷. Project allows to move the camera while animated 3D story is rendered for music. After movie is over user is allowed to create 3D models that are later incorporated into experiences of next people watching. This way interactions and social element are enabled in what used to be one-way transmission of art form.

Rysunek 6.3: Screenshot from "3 dreams of black"



⁷<http://www.ro.me/>

6.1. Encountered environment limitations

6.2. Browser advantages

6.3. Recommended techniques

6.4. Final thoughts

A. Acknowledgements

This publication expresses my personal experiences and opinions, not those of my employer or co-workers. No internal information was used in process of writing. Any errors in benchmark approach, code and factual content of publication are solely my responsibility.

Work is shared under MIT license and hosted online at <https://github.com/fridek/Thesis-physics>

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B. Source code

B.1. Math utilities

```
1 /**
2  * @fileoverview Math utils.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4  */
5
6 goog.provide('smash.math');
7
8
9 /**
10  * @param {number} x
11  * @return {number}
12  */
13 smash.math.square = function(x) {
14     return x * x;
15 };
16
17
18 /**
19  * @param {number} x1
20  * @param {number} y1
21  * @param {number} z1
22  * @param {number} x2
23  * @param {number} y2
24  * @param {number} z2
25  * @return {number}
26  */
27 smash.math.vectorDistance = function(x1, y1, z1, x2, y2, z2) {
28     return Math.sqrt(smash.math.square(x1 - x2) +
29                     smash.math.square(y1 - y2) +
30                     smash.math.square(z1 - z2));
31 };
32
33
34 /**
35  * @param {number} x
36  * @param {number} y
37  * @param {number} z
38  * @return {number}
39  */
```

```

40 smash.math.vectorLength = function(x, y, z) {
41     return Math.sqrt(smash.math.square(x) +
42         smash.math.square(y) +
43         smash.math.square(z));
44 };
45
46
47 /**
48 * @param {!smash.Sphere} sphere1
49 * @param {!smash.Sphere} sphere2
50 * @return {boolean}
51 */
52 smash.math.checkCollidingSpheres = function(sphere1, sphere2) {
53     return smash.math.vectorDistance(
54         sphere1.positionX, sphere1.positionY, sphere1.positionZ,
55         sphere2.positionX, sphere2.positionY, sphere2.positionZ) <
56         sphere1.radius + sphere2.radius;
57 };

```

Listing B.1: Math utilities in JavaScript

```

1 #include "math.h"
2
3
4 /**
5 * @param {number} x
6 * @return {number}
7 */
8 float smash::math::square(float x) {
9     return x * x;
10 }
11
12
13 /**
14 * @param {number} x1
15 * @param {number} y1
16 * @param {number} z1
17 * @param {number} x2
18 * @param {number} y2
19 * @param {number} z2
20 * @return {number}
21 */
22 float smash::math::vectorDistance(float x1, float y1, float z1, float x2, float y2, float z2) {
23     return sqrt(smash::math::square(x1 - x2) +
24         smash::math::square(y1 - y2) +
25         smash::math::square(z1 - z2));
26 }
27
28
29 /**
30 * @param {number} x
31 * @param {number} y
32 * @param {number} z
33 * @return {number}
34 */

```

```
35 float smash::math::vectorLength(float x, float y, float z) {
36     return sqrt(smash::math::square(x) +
37                 smash::math::square(y) +
38                 smash::math::square(z));
39 }
40
41
42 /**
43 * @param {!smash.Sphere} sphere1
44 * @param {!smash.Sphere} sphere2
45 * @return {boolean}
46 */
47 bool smash::math::checkCollidingSpheres(smash::Sphere* sphere1, smash::Sphere* sphere2) {
48     return smash::math::vectorDistance(
49         sphere1->positionX, sphere1->positionY, sphere1->positionZ,
50         sphere2->positionX, sphere2->positionY, sphere2->positionZ) <
51         sphere1->radius + sphere2->radius;
52 }
```

Listing B.2: Math utilities in C++

B.2. Particle system

```
1 /**
2  * @fileoverview Particle object.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4  */
5
6 goog.provide('smash.Particle');
7
8 /**
9  * @struct
10 * @constructor
11 */
12 smash.Particle = function() {
13 /**
14  * @type {number}
15 */
16 this.positionX = 0.1;
17
18 /**
19  * @type {number}
20 */
21 this.positionY = 0.1;
22
23 /**
24  * @type {number}
25 */
26 this.velocityX = 0.1;
27
28 /**
29  * @type {number}
30 */
31 this.velocityY = 0.1;
32
33 /**
34  * @type {number}
35 */
36 this.age = 0;
37
38 /**
39  * In seconds.
40  * @type {number}
41 */
42 this.lifespan = 0;
43
44 /**
45  * @type {boolean}
46 */
47 this.isDead = false;
48 };
49
50 /**
51 *
52 */
```

```

53 | smash.Particle.prototype.step = function() {
54 |   this.positionX += this.velocityX;
55 |   this.positionY += this.velocityY;
56 |   this.age++;
57 | };
58 |
59 |
60 | /**
61 | * Recover defaults.
62 | */
63 | smash.Particle.prototype.reset = function() {
64 |   this.positionX = 0;
65 |   this.positionY = 0;
66 |   this.velocityX = 0;
67 |   this.velocityY = 0;
68 |   this.age = 0;
69 |   this.lifespan = 0;
70 |   this.isDead = false;
71 | };

```

Listing B.3: Particle object in JavaScript

```

1 | /**
2 | * @fileoverview Particle object.
3 | * @author sebastian.poreba@gmail.com (Sebastian Poreba)
4 | */
5 | #include "particle.h"
6 |
7 | smash::Particle::Particle() {
8 |   positionX = 0;
9 |   positionY = 0;
10 |  velocityX = 0;
11 |  velocityY = 0;
12 |  age = 0;
13 |  lifespan = 0;
14 |  isDead = false;
15 | }
16 |
17 | /**
18 | * @param deltaTime
19 | */
20 | void smash::Particle::step() {
21 |   this->positionX += this->velocityX;
22 |   this->positionY += this->velocityY;
23 |   this->age++;
24 | }
25 |
26 |
27 | /**
28 | * Recover defaults.
29 | */
30 | void smash::Particle::reset() {
31 |   this->positionX = 0;
32 |   this->positionY = 0;
33 |   this->velocityX = 0;

```

```

34     this->velocityY = 0;
35     this->age = 0;
36     this->lifespan = 0;
37     this->isDead = false;
38 }

```

Listing B.4: Particle object in C++

```

1 /**
2  * @fileoverview Particle emitter.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4 */
5
6 goog.provide('smash.ParticleEmitter');
7
8 goog.require('smash.Particle');
9
10 /**
11  * @constructor
12 */
13 smash.ParticleEmitter = function() {
14 /**
15  * @type {number}
16 */
17 this.positionX = 0.1;
18
19 /**
20  * @type {number}
21 */
22 this.positionY = 0.1;
23
24 /**
25  * @type {number}
26 */
27 this.angle = 0.1;
28
29 /**
30  * @type {number}
31 */
32 this.velocity = 10.1;
33
34 /**
35  * @type {number}
36 */
37 this.velocitySpread = 0.2;
38
39 /**
40  * @type {number}
41 */
42 this.spread = Math.PI * 10 / 180;
43
44 /**
45  * In ticks.
46  * @type {number}
47 */

```

```
48     this.lifespan = 50;
49
50     /**
51      * @type {number}
52      */
53     this.productionRate = 10;
54 };
55
56
57 /**
58  * @param {number} angle
59  */
60 smash.ParticleEmitter.prototype.setAngle = function(angle) {
61     this.angle = Math.PI * angle / 180;
62 };
63
64
65 /**
66  * @param {number} velocity
67  */
68 smash.ParticleEmitter.prototype.setVelocity = function(velocity) {
69     this.velocity = velocity;
70 };
71
72
73 /**
74  * @param {number} velocitySpread
75  */
76 smash.ParticleEmitter.prototype.setVelocitySpread = function(velocitySpread) {
77     this.velocitySpread = velocitySpread;
78 };
79
80
81 /**
82  * @param {number} spread
83  */
84 smash.ParticleEmitter.prototype.setSpread = function(spread) {
85     this.spread = Math.PI * spread / 180;
86 };
87
88
89 /**
90  * @param {number} lifespan
91  */
92 smash.ParticleEmitter.prototype.setLifespan = function(lifespan) {
93     this.lifespan = lifespan;
94 };
95
96
97 /**
98  * @param {number} rate
99  */
100 smash.ParticleEmitter.prototype.setProductionRate = function(rate) {
101     this.productionRate = rate;
102 };
103
104
```

```

105 /**
106 * @return {!Array.<!smash.Particle>}
107 */
108 smash.ParticleEmitter.prototype.getNewParticles = function() {
109   var newParticles = [];
110   for (var i = 0; i < this.productionRate; i++) {
111     var p = new smash.Particle();
112     p.lifespan = this.lifespan;
113     p.positionX = this.positionX;
114     p.positionY = this.positionY;
115     p.velocityX = Math.sin(this.angle +
116       (Math.random() - 0.5) * this.spread) *
117       this.velocity * this.velocitySpread;
118     p.velocityY = Math.cos(this.angle +
119       (Math.random() - 0.5) * this.spread) *
120       this.velocity *
121       (1 + (Math.random() - 0.5) * this.velocitySpread);
122     newParticles.push(p);
123   }
124   return newParticles;
125 };

```

Listing B.5: Particle emitter object in JavaScript

```

1 /**
2 * @fileoverview Particle emitter.
3 * @author sebastian.poreba@gmail.com (Sebastian Poreba)
4 */
5 #include "particleEmitter.h"
6
7 smash::ParticleEmitter::ParticleEmitter() {
8   positionX = 0;
9   positionY = 0;
10  angle = 0;
11  velocity = 10;
12  velocitySpread = 0.2;
13  spread = M_PI * 10 / 180;
14  lifespan = 50;
15  productionRate = 10;
16 };
17
18
19 /**
20 * @param angle
21 */
22 void smash::ParticleEmitter::setAngle(float angle) {
23   this->angle = M_PI * angle / 180;
24 };
25
26
27 /**
28 * @param velocity
29 */
30 void smash::ParticleEmitter::setVelocity(float velocity) {
31   this->velocity = velocity;

```

```
32 };
33
34
35 /**
36 * @param velocitySpread
37 */
38 void smash::ParticleEmitter::setVelocitySpread(float velocitySpread) {
39     this->velocitySpread = velocitySpread;
40 }
41
42 /**
43 * @param spread
44 */
45 void smash::ParticleEmitter::setSpread(float spread) {
46     this->spread = M_PI * spread / 180;
47 }
48
49
50 /**
51 * @param lifespan
52 */
53 void smash::ParticleEmitter::setLifespan(float lifespan) {
54     this->lifespan = lifespan;
55 }
56
57
58 /**
59 * @param rate
60 */
61 void smash::ParticleEmitter::setProductionRate(int rate) {
62     this->productionRate = rate;
63 }
64
65
66 /**
67 * @return {!Array.<!smash::Particle>}
68 */
69 std::vector<smash::Particle*>* smash::ParticleEmitter::getNewParticles() {
70     std::vector<smash::Particle*> *newParticles = new std::vector<smash::Particle*>;
71     for (int i = 0; i < this->productionRate; i++) {
72         smash::Particle* p = new smash::Particle();
73         p->lifespan = this->lifespan;
74         p->positionX = this->positionX;
75         p->positionY = this->positionY;
76         p->velocityX = sin(this->angle +
77             ((float) rand() / (RAND_MAX)) - 0.5) * this->spread) *
78             this->velocity *
79             (1 + (((float) rand() / (RAND_MAX)) - 0.5) * this->velocitySpread);
80         p->velocityY = cos(this->angle +
81             ((float) rand() / (RAND_MAX)) - 0.5) * this->spread) *
82             this->velocity *
83             (1 + (((float) rand() / (RAND_MAX)) - 0.5) * this->velocitySpread);
84         newParticles->push_back(p);
85     }
86 }
87 return newParticles;
88 }
```

Listing B.6: Particle emitter object in C++

```
1 /**
2  * @fileoverview Particle system.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4  */
5
6 goog.provide('smash.ParticleSystem');
7
8 goog.require('smash.Particle');
9 goog.require('smash.ParticleEmitter');
10
11 /**
12  * @constructor
13  */
14 smash.ParticleSystem = function() {
15 /**
16  * @type {!Array.<smash.Particle>}
17  */
18 this.particles = [];
19
20 /**
21  * @type {!Array.<smash.ParticleEmitter>}
22  */
23 this.emitters = [];
24
25 if (smash.ParticleSystem.DRAWING_ENABLED) {
26 /**
27  * @type {!Element}
28  */
29 this.canvas = window.document.createElement("canvas");
30 this.canvas.width = smash.ParticleSystem.CANVAS_WIDTH;
31 this.canvas.height = smash.ParticleSystem.CANVAS_HEIGHT;
32 window.document.body.appendChild(this.canvas);
33
34 /**
35  * @type {!CanvasRenderingContext2D}
36  */
37 this.context = this.canvas.getContext('2d');
38
39 /**
40  * @type {!ImageData}
41  */
42 this.imageData = this.context.getImageData(0, 0,
43 smash.ParticleSystem.CANVAS_WIDTH, smash.ParticleSystem.CANVAS_HEIGHT);
44
45 /**
46  * @type {!CanvasPixelArray}
47  */
48 this.pixels = this.imageData.data;
49 }
50 };
51
52 /**
```

```
53 * @const {boolean}
54 */
55 smash.ParticleSystem.DRAWING_ENABLED = false;
56
57 /**
58 * @const {number}
59 */
60 smash.ParticleSystem.CANVAS_WIDTH = 1200;
61
62 /**
63 * @const {number}
64 */
65 smash.ParticleSystem.CANVAS_HEIGHT = 400;
66
67
68 smash.ParticleSystem.prototype.step = function() {
69   if (smash.ParticleSystem.DRAWING_ENABLED) {
70     for (var i = 0; i < smash.ParticleSystem.CANVAS_WIDTH *
71       smash.ParticleSystem.CANVAS_HEIGHT * 4; i+=4) {
72       this.pixels[i] = 0;
73       this.pixels[i + 1] = 0;
74       this.pixels[i + 2] = 0;
75       this.pixels[i + 3] = 0;
76     }
77   }
78
79   this.emitters.forEach(function(emitter) {
80     this.particles.push.apply(this.particles,
81       emitter.getNewParticles());
82   }, this);
83
84   var newParticles = [];
85   this.particles.forEach(function(p) {
86     p.step();
87     if (p.positionX >= 0 &&
88       p.positionX < smash.ParticleSystem.CANVAS_WIDTH &&
89       p.positionY >= 0 &&
90       p.positionY < smash.ParticleSystem.CANVAS_HEIGHT &&
91       p.age < p.lifespan) {
92       newParticles.push(p);
93     }
94
95     if (smash.ParticleSystem.DRAWING_ENABLED) {
96       var baseIndex =
97         (Math.round(p.positionY) *
98          smash.ParticleSystem.CANVAS_WIDTH +
99          Math.round(p.positionX)) * 4;
100      this.pixels[baseIndex] = 255;
101      this.pixels[baseIndex + 1] = 0;
102      this.pixels[baseIndex + 2] = 0;
103      this.pixels[baseIndex + 3] = 255;
104    }
105  }, this);
106  if (smash.ParticleSystem.DRAWING_ENABLED) {
107    this.context.putImageData(this.imageData, 0, 0);
108  }
109}
```

```

110   this.particles = newParticles;
111   window.console.log(this.particles.length);
112 };
113
114 /**
115 * @param {!smash.ParticleEmitter} emitter
116 */
117 smash.ParticleSystem.prototype.addEmitter = function(emitter) {
118   this.emitters.push(emitter);
119 };

```

Listing B.7: Initial particle system object in JavaScript

```

1 /**
2  * @fileoverview Particle system.
3  * @author sebastian.poreba@gmail.com (Sebastian Poreba)
4 */
5 #include "particleSystem.h"
6
7 smash::ParticleSystem::ParticleSystem() {
8   this->particles = new std::vector<smash::Particle*>;
9   this->emitters = new std::vector<smash::ParticleEmitter*>;
10 };
11
12 smash::ParticleSystem::~ParticleSystem() {
13   this->particles->erase(this->particles->begin(), this->particles->end());
14   delete this->particles;
15   this->emitters->erase(this->emitters->begin(), this->emitters->end());
16   delete this->emitters;
17 };
18
19 void smash::ParticleSystem::step() {
20   for (std::vector<smash::ParticleEmitter*>::iterator it = this->emitters->begin(); it != this->emitters->end();
21        ++it) {
22     smash::Particle* particleFromEmitters = (*it)->getNewParticles();
23     this->particles->insert(this->particles->end(), particleFromEmitters->begin(), particleFromEmitters->end());
24   }
25
26   std::vector<smash::Particle*> newParticles = new std::vector<smash::Particle*>;
27   for (std::vector<smash::Particle*>::iterator it = this->particles->begin(); it != this->particles->end();
28        ++it) {
29     smash::Particle* p = *it;
30     p->step();
31     if (p->positionX >= 0 &&
32         p->positionX < smash::ParticleSystem::CANVAS_WIDTH &&
33         p->positionY >= 0 &&
34         p->positionY < smash::ParticleSystem::CANVAS_HEIGHT &&
35         p->age < p->lifespan) {
36       newParticles->push_back(p);
37     }
38   };
39   this->particles = newParticles;
40 };
41 /**
42 * @param emitter
43 */

```

```

43 void smash::ParticleSystem::addEmitter(smash::ParticleEmitter* emitter) {
44     this->emitters->push_back(emitter);
45 }

```

Listing B.8: Initial particle system in C++

```

1 /**
2  * @fileoverview Particle system.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4  */
5
6 goog.provide('smash.ParticleSystem2');
7
8 goog.require('smash.Particle');
9 goog.require('smash.ParticleEmitter');
10
11
12 /**
13  * @constructor
14  */
15 smash.ParticleSystem2 = function() {
16     /**
17      * @type {!Array.<smash.Particle>}
18      */
19     this.particles = [];
20
21     /**
22      * @type {!Array.<number>}
23      */
24     this.deadParticles = [];
25
26     /**
27      * @type {!Array.<smash.ParticleEmitter>}
28      */
29     this.emitters = [];
30
31     if (smash.ParticleSystem2.DRAWING_ENABLED) {
32         /**
33          * @type {!Element}
34          */
35         this.canvas = window.document.createElement("canvas");
36         this.canvas.width = smash.ParticleSystem2.CANVAS_WIDTH;
37         this.canvas.height = smash.ParticleSystem2.CANVAS_HEIGHT;
38         window.document.body.appendChild(this.canvas);
39
40         /**
41          * @type {!CanvasRenderingContext2D}
42          */
43         this.context = this.canvas.getContext('2d');
44
45         /**
46          * @type {!ImageData}
47          */
48         this.imageData = this.context.getImageData(0, 0,
49                                         smash.ParticleSystem2.CANVAS_WIDTH, smash.ParticleSystem2.CANVAS_HEIGHT);

```

```
50  /**
51   * @type {!CanvasPixelArray}
52   */
53   this.pixels = this.imageData.data;
54 }
55 };
56
57 /**
58 * @const {boolean}
59 */
60
61 smash.ParticleSystem2.DRAWING_ENABLED = true;
62
63 /**
64 * @const {number}
65 */
66 smash.ParticleSystem2.CANVAS_WIDTH = 1200;
67
68 /**
69 * @const {number}
70 */
71 smash.ParticleSystem2.CANVAS_HEIGHT = 400;
72
73
74 smash.ParticleSystem2.prototype.step = function() {
75   if (smash.ParticleSystem2.DRAWING_ENABLED) {
76     for (var i = 0; i < smash.ParticleSystem2.CANVAS_WIDTH *
77       smash.ParticleSystem2.CANVAS_HEIGHT * 4; i+=4) {
78       this.pixels[i] = 0;
79       this.pixels[i + 1] = 0;
80       this.pixels[i + 2] = 0;
81       this.pixels[i + 3] = 0;
82     }
83   }
84
85   for (var ei = 0; ei < this.emitters.length; ei++) {
86     var emitter = this.emitters[ei];
87     for (var i = 0; i < emitter.productionRate; i++) {
88       var pIndex = this.deadParticles.pop();
89       if (pIndex !== undefined) {
90         var p = this.particles[pIndex];
91         p.reset();
92       } else {
93         var p = new smash.Particle();
94         this.particles.push(p);
95       }
96
97       p.lifespan = emitter.lifespan;
98       p.positionX = emitter.positionX;
99       p.positionY = emitter.positionY;
100      p.velocityX = Math.sin(emitter.angle +
101        (Math.random() - 0.5) * emitter.spread) *
102        emitter.velocity * emitter.velocitySpread;
103      p.velocityY = Math.cos(emitter.angle +
104        (Math.random() - 0.5) * emitter.spread) *
105        emitter.velocity *
106        (1 + (Math.random() - 0.5) * emitter.velocitySpread);
```

```

107     }
108 }
109
110 for (var i = 0; i < this.particles.length; i++) {
111     var p = this.particles[i];
112     p.step();
113     if (p.positionX < 0 ||
114         p.positionX >= smash.ParticleSystem2.CANVAS_WIDTH ||
115         p.positionY < 0 ||
116         p.positionY >= smash.ParticleSystem2.CANVAS_HEIGHT ||
117         p.age > p.lifespan) {
118         this.deadParticles.push(i);
119         p.isDead = true;
120     }
121
122     if (smash.ParticleSystem2.DRAWING_ENABLED && !p.isDead) {
123         var baseIndex =
124             (Math.round(p.positionY) *
125              smash.ParticleSystem2.CANVAS_WIDTH +
126              Math.round(p.positionX)) * 4;
127         this.pixels[baseIndex] = Math.round(p.velocityX * 80);
128         this.pixels[baseIndex + 1] = Math.round(p.velocityX * 80);
129         this.pixels[baseIndex + 2] = 255 - Math.round(p.age / p.lifespan * 255);
130         this.pixels[baseIndex + 3] = 255;
131     }
132 }
133
134 if (smash.ParticleSystem2.DRAWING_ENABLED) {
135     this.context.putImageData(this.imageData, 0, 0);
136 }
137 };
138
139 /**
140 * @param {!smash.ParticleEmitter} emitter
141 */
142 smash.ParticleSystem2.prototype.addEmitter = function(emitter) {
143     this.emitters.push(emitter);
144 };

```

Listing B.9: Optimised particle system object in JavaScript

```

1 /**
2  * @fileoverview Particle system.
3  * @author sebastian.poreba@gmail.com (Sebastian Poreba)
4  */
5 #include "particleSystem2.h"
6
7 smash::ParticleSystem2::ParticleSystem2() {
8     this->particles = new std::vector<smash::Particle*>;
9     this->deadParticles = new std::stack<smash::Particle*>;
10    this->emitters = new std::vector<smash::ParticleEmitter*>;
11 };
12
13 smash::ParticleSystem2::~ParticleSystem2() {
14     this->particles->erase(this->particles->begin(), this->particles->end());

```

```

15    delete this->particles;
16    while (!this->deadParticles->empty()) {
17        delete this->deadParticles->top();
18        this->deadParticles->pop();
19    }
20    delete this->deadParticles;
21    this->emitters->erase(this->emitters->begin(), this->emitters->end());
22    delete this->emitters;
23 };
24
25 void smash::ParticleSystem2::step() {
26     for (std::vector<smash::ParticleEmitter*>::iterator it = this->emitters->begin(); it != this->emitt
27         smash::ParticleEmitter* emitter = *it;
28         for (int i = 0; i < emitter->productionRate; i++) {
29             smash::Particle* p;
30             if (!this->deadParticles->empty()) {
31                 p = this->deadParticles->top();
32                 this->deadParticles->pop();
33                 p->reset();
34             } else {
35                 p = new smash::Particle();
36                 this->particles->push_back(p);
37             }
38
39             p->lifespan = emitter->lifespan;
40             p->positionX = emitter->positionX;
41             p->positionY = emitter->positionY;
42             p->velocityX = sin(emitter->angle +
43                 (((float) rand() / (RAND_MAX)) - 0.5) * emitter->spread) *
44                 emitter->velocity *
45                 (1 + (((float) rand() / (RAND_MAX)) - 0.5) * emitter->velocitySpread);
46             p->velocityY = cos(emitter->angle +
47                 (((float) rand() / (RAND_MAX)) - 0.5) * emitter->spread) *
48                 emitter->velocity *
49                 (1 + (((float) rand() / (RAND_MAX)) - 0.5) * emitter->velocitySpread);
50         }
51     }
52
53     for (std::vector<smash::Particle*>::iterator it = this->particles->begin(); it != this->particles->
54         smash::Particle* p = *it;
55         if (p->isDead) {
56             continue;
57         }
58         p->step();
59         if (p->positionX < 0 ||
60             p->positionX >= smash::ParticleSystem2::CANVAS_WIDTH ||
61             p->positionY < 0 ||
62             p->positionY >= smash::ParticleSystem2::CANVAS_HEIGHT ||
63             p->age > p->lifespan) {
64             this->deadParticles->push(p);
65             p->isDead = true;
66         }
67     };
68 };
69
70 /**
71 * @param emitter

```

```
72 */  
73 void smash::ParticleSystem2::addEmitter(smash::ParticleEmitter* emitter) {  
74     this->emitters->push_back(emitter);  
75 }
```

Listing B.10: Optimised particle system in C++

B.3. Spheres collision detection

```
1 /**
2  * @fileoverview Sphere file.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4  */
5
6
7 goog.provide('smash.Sphere');
8
9
10
11 /**
12  * @struct
13  * @constructor
14  */
15 smash.Sphere = function() {
16 /**
17  * @type {number}
18  */
19 this.positionX = 0.1;
20
21 /**
22  * @type {number}
23  */
24 this.positionY = 0.1;
25
26 /**
27  * @type {number}
28  */
29 this.positionZ = 0.1;
30
31 /**
32  * @type {number}
33  */
34 this.velocityX = 0.1;
35
36 /**
37  * @type {number}
38  */
39 this.velocityY = 0.1;
40
41 /**
42  * @type {number}
43  */
44 this.velocityZ = 0.1;
45
46 /**
47  * @type {number}
48  */
49 this.radius = 5.5;
50 };
51
52
```

```

53 /**
54 *
55 */
56 smash.Sphere.prototype.step = function(stepTime) {
57   this.positionX += this.velocityX * stepTime;
58   this.positionY += this.velocityY * stepTime;
59   this.positionZ += this.velocityZ * stepTime;
60 };

```

Listing B.11: Sphere object in JavaScript

```

1 /**
2  * @fileoverview Sphere file.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4 */
5
6 #include "sphere.h"
7
8 smash::Sphere::Sphere() {
9   positionX = 0;
10  positionY = 0;
11  positionZ = 0;
12  velocityX = 0;
13  velocityY = 0;
14  velocityZ = 0;
15  radius = 5.5;
16 };
17
18 /**
19  * @param stepTime
20 */
21 void smash::Sphere::step(float stepTime) {
22   this->positionX += this->velocityX * stepTime;
23   this->positionY += this->velocityY * stepTime;
24   this->positionZ += this->velocityZ * stepTime;
25 };

```

Listing B.12: Sphere object in C++

```

1 /**
2  * @fileoverview Sphere collision detection system.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4 */
5
6 goog.provide('smash.SphereSystem');
7
8 goog.require('smash.Sphere');
9 goog.require('smash.math');
10
11
12
13 /**
14  * @constructor
15 */

```

```
16 | smash.SphereSystem = function() {
17 |   var generalVelocity = 1;
18 |   /**
19 |     * @type {!Array.<!smash.Sphere>}
20 |   */
21 |   this.spheres = new Array(smash.SphereSystem.SPHERES_COUNT);
22 |   for (var i = 0; i < smash.SphereSystem.SPHERES_COUNT; i++) {
23 |     var sphere = new smash.Sphere();
24 |     sphere.positionX = (Math.random() - 0.5) * 400;
25 |     sphere.positionY = (Math.random() - 0.5) * 200;
26 |     sphere.positionZ = (Math.random() - 0.5) * 100;
27 |     sphere.velocityX = (Math.random() - 0.5) * generalVelocity;
28 |     sphere.velocityY = (Math.random() - 0.5) * generalVelocity;
29 |     sphere.velocityZ = (Math.random() - 0.5) * generalVelocity;
30 |     this.spheres[i] = sphere;
31 |   }
32 |
33 |   if (smash.SphereSystem.DRAWING_ENABLED) {
34 |     /**
35 |       * @type {!THREE.PerspectiveCamera}
36 |     */
37 |     this.camera = new THREE.PerspectiveCamera(20,
38 |       smash.SphereSystem.CANVAS_WIDTH /
39 |         smash.SphereSystem.CANVAS_HEIGHT,
40 |         1, 10000);
41 |     this.camera.position.z = 1000;
42 |
43 |     var controls = new THREE.OrbitControls(this.camera);
44 |     controls.addEventListener('change', goog.bind(function() {
45 |       this.renderer.render(this.scene, this.camera);
46 |     }, this));
47 |
48 |     /**
49 |       * @type {!THREE.Scene}
50 |     */
51 |     this.scene = new THREE.Scene();
52 |
53 |     var spotLight = new THREE.PointLight(0xffffffff);
54 |     spotLight.position.set(-40, 60, -10);
55 |     this.scene.add(spotLight);
56 |
57 |     var axes = new THREE.AxisHelper(20);
58 |     this.scene.add(axes);
59 |
60 |     var planeGeometry = new THREE.PlaneGeometry(
61 |       10000, 10000, 100, 100);
62 |     var planeMaterial = new THREE.MeshBasicMaterial({
63 |       color: 0xcccccc,
64 |       wireframe: true
65 |     });
66 |
67 |     var plane = new THREE.Mesh(planeGeometry, planeMaterial);
68 |     plane.rotation.x = -0.5 * Math.PI;
69 |     plane.position.x = 0;
70 |     plane.position.y = smash.SphereSystem.FLOOR_LEVEL;
71 |     plane.position.z = 0;
72 | }
```

```
73     this.scene.add(plane);
74
75
76
77     var material = new THREE.MeshLambertMaterial({
78         color: 0xff0000
79     });
80     /**
81      * @type {!Array.<!THREE.SphereGeometry>}
82     */
83     this.threeSpheres = new Array(smash.SphereSystem.SPHERES_COUNT);
84     for (var i = 0; i < smash.SphereSystem.SPHERES_COUNT; i++) {
85         var sphere = new THREE.SphereGeometry(this.spheres[i].radius, 10, 10);
86         var mesh = new THREE.Mesh(sphere, material);
87         mesh.position.x = this.spheres[i].positionX;
88         mesh.position.y = this.spheres[i].positionY;
89         mesh.position.z = this.spheres[i].positionZ;
90         this.threeSpheres[i] = mesh;
91
92         this.scene.add(mesh);
93     }
94
95
96
97     /**
98      * @type {!THREE.WebGLRenderer}
99     */
100    this.renderer = new THREE.WebGLRenderer();
101    this.renderer.setSize(smash.SphereSystem.CANVAS_WIDTH,
102        smash.SphereSystem.CANVAS_HEIGHT);
103    document.body.appendChild(this.renderer.domElement);
104    this.renderer.render(this.scene, this.camera);
105 }
106
107 /**
108  * @type {number}
109 */
110 this.collisions = 0;
111 };
112
113
114 /**
115  * @const {number}
116 */
117 smash.SphereSystem.SPHERES_COUNT = 1000;
118
119
120 /**
121  * @const {boolean}
122 */
123 smash.SphereSystem.DRAWING_ENABLED = false;
124
125
126 /**
127  * @const {boolean}
128 */
129 smash.SphereSystem.GRAVITY_ENABLED = true;
```

```
130
131
132 /**
133 * @const {number}
134 */
135 smash.SphereSystem.GRAVITY_FORCE = 0.1;
136
137
138 /**
139 * @const {number}
140 */
141 smash.SphereSystem.FLOOR_LEVEL = -100;
142
143
144 /**
145 * (1 - energy lost on floor hit)
146 * @const {number}
147 */
148 smash.SphereSystem.FLOOR_FRICTION = 0.8;
149
150
151 /**
152 * @const {number}
153 */
154 smash.SphereSystem.CANVAS_WIDTH = 1200;
155
156
157 /**
158 * @const {number}
159 */
160 smash.SphereSystem.CANVAS_HEIGHT = 400;
161
162
163 /**
164 * @param {!smash.Sphere} sphere1
165 * @param {!smash.Sphere} sphere2
166 */
167 smash.SphereSystem.collide = function(sphere1, sphere2) {
168     var sumVelocitiesLength = smash.math.vectorLength(
169         sphere1.velocityX, sphere1.velocityY, sphere1.velocityZ) +
170         smash.math.vectorLength(
171             sphere2.velocityX, sphere2.velocityY, sphere2.velocityZ);
172
173     var centerDiffX = sphere1.positionX - sphere2.positionX;
174     var centerDiffY = sphere1.positionY - sphere2.positionY;
175     var centerDiffZ = sphere1.positionZ - sphere2.positionZ;
176     var centerLength = smash.math.vectorLength(
177         centerDiffX, centerDiffY, centerDiffZ);
178     var velocityAdjust = centerLength * sumVelocitiesLength / 2;
179     centerDiffX /= velocityAdjust;
180     centerDiffY /= velocityAdjust;
181     centerDiffZ /= velocityAdjust;
182
183     sphere1.velocityX = centerDiffX;
184     sphere1.velocityY = centerDiffY;
185     sphere1.velocityZ = centerDiffZ;
186     sphere2.velocityX = centerDiffX * -1;
```

```

187     sphere2.velocityY = centerDiffY * -1;
188     sphere2.velocityZ = centerDiffZ * -1;
189 };
190
191
192 /**
193 * @param {!smash.Sphere} sphere
194 */
195 smash.SphereSystem.prototype.applyGravity = function(sphere) {
196   if (smash.SphereSystem.GRAVITY_ENABLED) {
197     sphere.velocityY -= smash.SphereSystem.GRAVITY_FORCE;
198   }
199 };
200
201
202 /**
203 * @param {!smash.Sphere} sphere
204 */
205 smash.SphereSystem.prototype.applyFloor = function(sphere) {
206   if (sphere.positionY - sphere.radius <
207       smash.SphereSystem.FLOOR_LEVEL) {
208     sphere.velocityY *= -smash.SphereSystem.FLOOR_FRICTION;
209   }
210 };
211
212
213 /**
214 *
215 */
216 smash.SphereSystem.prototype.step = function() {
217   for (var i = 0; i < smash.SphereSystem.SPHERES_COUNT; i++) {
218     this.applyGravity(this.spheres[i]);
219     this.applyFloor(this.spheres[i]);
220
221     this.spheres[i].step(1);
222     for (var j = 0; j < smash.SphereSystem.SPHERES_COUNT; j++) {
223       if (i != j &&
224           smash.math.checkCollidingSpheres(this.spheres[i], this.spheres[j])) {
225         this.collisions++;
226         smash.SphereSystem.collide(this.spheres[i], this.spheres[j]);
227       }
228     }
229   }
230
231   if (smash.SphereSystem.DRAWING_ENABLED) {
232     this.threeSpheres[i].position.x = this.spheres[i].positionX;
233     this.threeSpheres[i].position.y = this.spheres[i].positionY;
234     this.threeSpheres[i].position.z = this.spheres[i].positionZ;
235   }
236 }
237
238   if (smash.SphereSystem.DRAWING_ENABLED) {
239     this.renderer.render(this.scene, this.camera);
240   }
241 };

```

Listing B.13: Sphere system object in JavaScript

```

1  /**
2   * @fileoverview Sphere collision detection system.
3   * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4   */
5
6 #include "sphereSystem.h"
7
8 smash::SphereSystem::SphereSystem() {
9     this->spheres = new std::vector<smash::Sphere*>;
10    collisions = 0;
11
12    float generalVelocity = 1;
13    for (int i = 0; i < smash::SphereSystem::SPHERES_COUNT; i++) {
14        smash::Sphere* sphere = new smash::Sphere();
15        sphere->positionX = (((float) rand() / (RAND_MAX)) - 0.5) * 400;
16        sphere->positionY = (((float) rand() / (RAND_MAX)) - 0.5) * 200;
17        sphere->positionZ = (((float) rand() / (RAND_MAX)) - 0.5) * 100;
18        sphere->velocityX = (((float) rand() / (RAND_MAX)) - 0.5) * generalVelocity;
19        sphere->velocityY = (((float) rand() / (RAND_MAX)) - 0.5) * generalVelocity;
20        sphere->velocityZ = (((float) rand() / (RAND_MAX)) - 0.5) * generalVelocity;
21        this->spheres->push_back(sphere);
22    }
23}
24
25
26 smash::SphereSystem::~SphereSystem() {
27     this->spheres->erase(this->spheres->begin(), this->spheres->end());
28     delete this->spheres;
29}
30
31
32 /**
33  * @param {smash::Sphere*} sphere1
34  * @param {smash::Sphere*} sphere2
35  */
36 void smash::SphereSystem::collide(smash::Sphere* sphere1, smash::Sphere* sphere2) {
37     float sumVelocitiesLength = smash::math::vectorLength(
38         sphere1->velocityX, sphere1->velocityY, sphere1->velocityZ) +
39         smash::math::vectorLength(
40             sphere2->velocityX, sphere2->velocityY, sphere2->velocityZ);
41
42     float centerDiffX = sphere1->positionX - sphere2->positionX;
43     float centerDiffY = sphere1->positionY - sphere2->positionY;
44     float centerDiffZ = sphere1->positionZ - sphere2->positionZ;
45     float centerLength = smash::math::vectorLength(
46         centerDiffX, centerDiffY, centerDiffZ);
47     float velocityAdjust = centerLength * sumVelocitiesLength / 2;
48     centerDiffX /= velocityAdjust;
49     centerDiffY /= velocityAdjust;
50     centerDiffZ /= velocityAdjust;
51
52     sphere1->velocityX = centerDiffX;
53     sphere1->velocityY = centerDiffY;
54     sphere1->velocityZ = centerDiffZ;
55     sphere2->velocityX = centerDiffX * -1;
56     sphere2->velocityY = centerDiffY * -1;

```

```

57     sphere2->velocityZ = centerDiffZ * -1;
58 }
59
60 void smash::SphereSystem::applyGravity(smash::Sphere* sphere) {
61     if (smash::SphereSystem::GRAVITY_ENABLED) {
62         sphere->velocityY -= smash::SphereSystem::GRAVITY_FORCE;
63     }
64 }
65
66
67 void smash::SphereSystem::applyFloor(smash::Sphere* sphere) {
68     if (sphere->positionY - sphere->radius <
69         smash::SphereSystem::FLOOR_LEVEL) {
70         sphere->velocityY *= -smash::SphereSystem::FLOOR_FRICTION;
71     }
72 }
73
74
75 void smash::SphereSystem::step() {
76     for (std::vector<smash::Sphere*>::iterator it = this->spheres->begin(); it != this->spheres->end();
77         smash::Sphere* s = *it,
78         applyGravity(s);
79         applyFloor(s);
80
81
82         s->step(1);
83         for (std::vector<smash::Sphere*>::iterator it2 = this->spheres->begin(); it2 != this->spheres->end();
84             smash::Sphere* s2 = *it2;
85             if (s != s2 &&
86                 smash::math::checkCollidingSpheres(s, s2)) {
87                 this->collisions++;
88                 smash::SphereSystem::collide(s, s2);
89             }
90         }
91     }
92 }

```

Listing B.14: Sphere system in C++

```

1 /**
2  * @fileoverview Octree space partitioning.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4 */
5
6 goog.provide('smash.Octree');
7
8 goog.require('goog.array');
9
10
11 /**
12  * @param left
13  * @param right
14  * @param top
15  * @param bottom
16  * @param near

```

```
17 * @param far
18 * @param maxDepth
19 * @constructor
20 */
21 smash.Octree = function(left, right, top, bottom, near, far, maxDepth) {
22     this.maxDepth = maxDepth;
23
24     this.childNodes = [];
25
26     this.left = left;
27
28     this.right = right;
29
30     this.top = top;
31
32     this.bottom = bottom;
33
34     this.near = near;
35
36     this.far = far;
37
38     this.objects = [];
39 };
40
41 /**
42 *
43 */
44 smash.Octree.prototype.split = function() {
45     var middleX = (this.left + this.right) / 2;
46     var middleY = (this.top + this.bottom) / 2;
47     var middleZ = (this.near + this.far) / 2;
48     var maxDepth = this.maxDepth - 1;
49
50     this.childNodes[0] = new smash.Octree(this.left, middleX, this.top, middleY, this.near, middleZ, maxDepth);
51     this.childNodes[1] = new smash.Octree(middleX, this.right, this.top, middleY, this.near, middleZ, maxDepth);
52
53     this.childNodes[2] = new smash.Octree(this.left, middleX, middleY, this.bottom, this.near, middleZ, maxDepth);
54     this.childNodes[3] = new smash.Octree(middleX, this.right, middleY, this.bottom, this.near, middleZ, maxDepth);
55
56     this.childNodes[4] = new smash.Octree(this.left, middleX, middleY, this.top, middleZ, this.far, maxDepth);
57     this.childNodes[5] = new smash.Octree(middleX, this.right, middleY, this.top, middleZ, this.far, maxDepth);
58
59     this.childNodes[6] = new smash.Octree(this.left, middleX, middleY, this.bottom, middleZ, this.far, maxDepth);
60     this.childNodes[7] = new smash.Octree(middleX, this.right, middleY, this.bottom, middleZ, this.far, maxDepth);
61 };
62
63 /**
64 *
65 * @return {boolean}
66 */
67 smash.Octree.prototype.hasAnyObjects = function() {
68     return this.objects.length > 0 ||
69         this.childNodes.some(function(node) {
70             return node.hasAnyObjects();
71         });
72 };
73 }
```

```
74 /**
75 *
76 * @param left
77 * @param right
78 * @param top
79 * @param bottom
80 * @param near
81 * @param far
82 * @return {Array}
83 */
84
85 smash.Octree.prototype.getAllOffsets = function(left, right, top, bottom, near, far) {
86     var middleX = (this.left + this.right) / 2;
87     var middleY = (this.top + this.bottom) / 2;
88     var middleZ = (this.near + this.far) / 2;
89
90     var offset = 0;
91     var bothX = false, bothY = false, bothZ = false;
92
93     if (left < middleX && right < middleX) {
94         offset += 0;
95     } else if (left > middleX && right > middleX) {
96         offset += 1;
97     } else {
98         bothX = true;
99     }
100
101    if (top < middleY && bottom < middleY) {
102        offset += 0;
103    } else if (top > middleY && bottom > middleY) {
104        offset += 2;
105    } else {
106        bothY = true;
107    }
108
109    if (near < middleZ && far < middleZ) {
110        offset += 0;
111    } else if (near > middleZ && far > middleZ) {
112        offset += 4;
113    } else {
114        bothZ = true;
115    }
116
117    var allOffsets = [offset];
118    if (bothZ) {
119        for (var i = 0, l = allOffsets.length; i < l; i++) {
120            allOffsets.push(allOffsets[i] + 4);
121        }
122    }
123    if (bothY) {
124        for (var i = 0, l = allOffsets.length; i < l; i++) {
125            allOffsets.push(allOffsets[i] + 2);
126        }
127    }
128    if (bothX) {
129        for (var i = 0, l = allOffsets.length; i < l; i++) {
130            allOffsets.push(allOffsets[i] + 1);
```

```

131     }
132   }
133   return allOffsets;
134 };
135
136
137 /**
138 *
139 * @param sphere
140 * @return {boolean}
141 */
142 smash.Octree.prototype.sphereLeft = function(sphere) {
143   return (sphere.positionX + sphere.radius < this.left ||
144           sphere.positionX - sphere.radius > this.right ||
145           sphere.positionY + sphere.radius < this.top ||
146           sphere.positionY - sphere.radius > this.bottom ||
147           sphere.positionZ + sphere.radius < this.near ||
148           sphere.positionZ - sphere.radius > this.far);
149 };
150
151
152 smash.Octree.prototype.removeSphere = function(sphere) {
153   goog.array.remove(this.objects, sphere);
154 };
155
156
157 smash.Octree.prototype.addSphere = function(sphere) {
158   if (this.objects.indexOf(sphere) != -1) {
159     return; // this happens when sphere is re-added from two
160     // different nodes after removal.
161   }
162
163   var left = sphere.positionX - sphere.radius;
164   var right = sphere.positionX + sphere.radius;
165   var top = sphere.positionY - sphere.radius;
166   var bottom = sphere.positionY + sphere.radius;
167   var near = sphere.positionZ - sphere.radius;
168   var far = sphere.positionZ + sphere.radius;
169
170   if (this.maxDepth == 0 || this.objects.length == 0) {
171     this.objects.push(sphere);
172   } else {
173     if (this.childNodes.length == 0) {
174       this.split();
175     }
176     var offsets = this.getAllOffsets(left, right, top, bottom, near, far);
177     offsets.forEach(function(offset) {
178       this.childNodes[offset].addSphere(sphere);
179     }, this);
180   }
181 };
182
183 smash.Octree.prototype.log = function() {
184   window.console.log('On level ', this.maxDepth,
185   ' octree node with ', this.objects.length, ' objects');
186   this.childNodes.forEach(function(node) {
187     node.log();

```

```
188 } );
189 }
```

Listing B.15: Octree in JavaScript

```

1 /**
2 * @fileoverview Octree space partitioning.
3 * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4 */
5
6 #include "octree.h"
7
8
9 smash::Octree::Octree(float left, float right,
10   float top, float bottom,
11   float near, float far,
12   int maxDepth) {
13   this->maxDepth = maxDepth;
14   this->childNodes = new std::vector<smash::Octree*>;
15   this->left = left;
16   this->right = right;
17   this->top = top;
18   this->bottom = bottom;
19   this->near = near;
20   this->far = far;
21   this->objects = new std::vector<smash::Sphere*>;
22 };
23
24 smash::Octree::~Octree() {
25   delete this->objects;
26   for (std::vector<smash::Octree*>::iterator it = this->childNodes->begin(); it != this->childNodes->
27     delete *it;
28   }
29   delete this->childNodes;
30 }
31
32 /**
33 *
34 */
35 void smash::Octree::split() {
36   float middleX = (this->left + this->right) / 2;
37   float middleY = (this->top + this->bottom) / 2;
38   float middleZ = (this->near + this->far) / 2;
39   int maxDepth = this->maxDepth - 1;
40
41   this->childNodes->push_back(new smash::Octree(this->left, middleX, this->top, middleY, this->near,
42   this->childNodes->push_back(new smash::Octree(middleX, this->right, this->top, middleY, this->near,
43
44   this->childNodes->push_back(new smash::Octree(this->left, middleX, middleY, this->bottom, this->near,
45   this->childNodes->push_back(new smash::Octree(middleX, this->right, middleY, this->bottom, this->near,
46
47   this->childNodes->push_back(new smash::Octree(this->left, middleX, this->top, middleZ, this->near,
48   this->childNodes->push_back(new smash::Octree(middleX, this->right, this->top, middleZ, this->near,
49
50   this->childNodes->push_back(new smash::Octree(this->left, middleX, middleY, this->bottom, middleZ,
```

```

51     this->childNodes->push_back(new smash::Octree(middleX, this->right, middleY, this->bottom, middleZ,
52 );
53
54     bool smash::Octree::hasAnyObjects() {
55         if (this->objects->size() > 0) {
56             return true;
57         }
58
59         for (std::vector<smash::Octree*>::iterator it = this->childNodes->begin(); it != this->childNodes->
60             if ((*it)->hasAnyObjects()) {
61                 return true;
62             }
63         }
64
65         return false;
66     };
67
68     int smash::Octree::getTotalObjectCount() {
69         int count = this->objects->size();
70
71         for (std::vector<smash::Octree*>::iterator it = this->childNodes->begin(); it != this->childNodes->
72             count += (*it)->getTotalObjectCount();
73         }
74
75         return count;
76     };
77
78     int smash::Octree::getTotalTreeSize() {
79         int count = this->childNodes->size();
80         for (std::vector<smash::Octree*>::iterator it = this->childNodes->begin(); it != this->childNodes->
81             count += (*it)->getTotalTreeSize();
82         }
83
84         return count;
85     };
86
87
88     std::vector<int>* smash::Octree::getAllOffsets(float left, float right, float top, float bottom, float
89         float middleX = (this->left + this->right) / 2;
90         float middleY = (this->top + this->bottom) / 2;
91         float middleZ = (this->near + this->far) / 2;
92
93         float offset = 0;
94         bool bothX = false, bothY = false, bothZ = false;
95
96         if (left < middleX && right < middleX) {
97             offset += 0;
98         } else if (left > middleX && right > middleX) {
99             offset += 1;
100        } else {
101            bothX = true;
102        }
103
104        if (top < middleY && bottom < middleY) {
105            offset += 0;
106        } else if (top > middleY && bottom > middleY) {
107            offset += 2;

```

```

108 } else {
109     bothY = true;
110 }
111
112 if (near < middleZ && far < middleZ) {
113     offset += 0;
114 } else if (near > middleZ && far > middleZ) {
115     offset += 4;
116 } else {
117     bothZ = true;
118 }
119
120 std::vector<int>* allOffsets = new std::vector<int>;
121 allOffsets->push_back(offset);
122
123 if (bothZ) {
124     for (std::vector<int>::iterator it = allOffsets->begin(),
125          itEnd = allOffsets->end(); it != itEnd; it++) {
126         int n = *it;
127         allOffsets->push_back(n + 4);
128     }
129 }
130 if (bothY) {
131     for (std::vector<int>::iterator it = allOffsets->begin(),
132          itEnd = allOffsets->end(); it != itEnd; it++) {
133         int n = *it;
134         allOffsets->push_back(n + 2);
135     }
136 }
137 if (bothX) {
138     for (std::vector<int>::iterator it = allOffsets->begin(),
139          itEnd = allOffsets->end(); it != itEnd; it++) {
140         int n = *it;
141         allOffsets->push_back(n + 1);
142     }
143 }
144 /*
145 if (allOffsets->size() > 1) {
146     std::cout << "offsets ";
147     for (std::vector<int>::iterator it = allOffsets->begin(),
148          itEnd = allOffsets->end(); it != itEnd; it++) {
149         std::cout << *it << " ";
150     }
151     std::cout << std::endl;
152 }*/
153 return allOffsets;
154 };
155
156 bool smash::Octree::sphereLeft(smash::Sphere *sphere) {
157     return (sphere->positionX + sphere->radius < this->left ||
158            sphere->positionX - sphere->radius > this->right ||
159            sphere->positionY + sphere->radius < this->top ||
160            sphere->positionY - sphere->radius > this->bottom ||
161            sphere->positionZ + sphere->radius < this->near ||
162            sphere->positionZ - sphere->radius > this->far);
163 };
164

```

```

165
166 void smash::Octree::removeSphere(smash::Sphere *sphere) {
167     this->objects->erase(std::remove(this->objects->begin(), this->objects->end(), sphere));
168 }
169
170
171 void smash::Octree::addSphere(smash::Sphere *sphere) {
172     if (std::find(this->objects->begin(), this->objects->end(), sphere) !=
173         this->objects->end()) {
174         return; // this happens when sphere is re-added from two
175         // different nodes after removal.
176     }
177
178     float left = sphere->positionX - sphere->radius;
179     float right = sphere->positionX + sphere->radius;
180     float top = sphere->positionY - sphere->radius;
181     float bottom = sphere->positionY + sphere->radius;
182     float near = sphere->positionZ - sphere->radius;
183     float far = sphere->positionZ + sphere->radius;
184
185     if (this->maxDepth == 0 || this->objects->size() == 0) {
186         this->objects->push_back(sphere);
187     } else {
188         if (this->childNodes->size() == 0) {
189             this->split();
190         }
191         std::vector<int> *offsets = this->getAllOffsets(left, right, top, bottom, near, far);
192         for (std::vector<int>::iterator it = offsets->begin(); it != offsets->end(); it++) {
193             int offset = *it;
194             if (offset > 8) {
195                 // weird offset, investigate
196                 continue;
197             }
198             this->childNodes->at(offset)->addSphere(sphere);
199         }
200     }
201 }

```

Listing B.16: Octree in C++

```

1 /**
2  * @fileoverview Sphere collision detection system.
3  * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4 */
5
6 goog.provide('smash.SphereSystem2');
7
8 goog.require('smash.Octree');
9 goog.require('smash.Sphere');
10 goog.require('smash.math');
11
12
13
14 /**
15  * @constructor

```

```

16  /*
17   smash.SphereSystem2 = function() {
18     var generalVelocity = 1;
19     /**
20      * @type {!Array.<!smash.Sphere>}
21     */
22     this.spheres = new Array(smash.SphereSystem2.SPHERES_COUNT);
23     for (var i = 0; i < smash.SphereSystem2.SPHERES_COUNT; i++) {
24       var sphere = new smash.Sphere();
25       sphere.positionX = (Math.random() - 0.5) * 400;
26       sphere.positionY = (Math.random() - 0.5) * 200;
27       sphere.positionZ = (Math.random() - 0.5) * 100;
28       sphere.velocityX = (Math.random() - 0.5) * generalVelocity;
29       sphere.velocityY = (Math.random() - 0.5) * generalVelocity;
30       sphere.velocityZ = (Math.random() - 0.5) * generalVelocity;
31       this.spheres[i] = sphere;
32     }
33
34     if (smash.SphereSystem2.DRAWING_ENABLED) {
35       /**
36        * @type {!THREE.PerspectiveCamera}
37       */
38       this.camera = new THREE.PerspectiveCamera(20,
39         smash.SphereSystem2.CANVAS_WIDTH /
40           smash.SphereSystem2.CANVAS_HEIGHT,
41           1, 10000);
42       this.camera.position.z = 1000;
43
44       var controls = new THREE.OrbitControls(this.camera);
45       controls.addEventListener('change', goog.bind(function() {
46         this.renderer.render(this.scene, this.camera);
47       }, this));
48
49       /**
50        * @type {!THREE.Scene}
51       */
52       this.scene = new THREE.Scene();
53
54       var spotLight = new THREE.PointLight(0xffffffff);
55       spotLight.position.set(-40, 60, -10);
56       this.scene.add(spotLight);
57
58       var axes = new THREE.AxisHelper(20);
59       this.scene.add(axes);
60
61       var planeGeometry = new THREE.PlaneGeometry(
62         10000, 10000, 100, 100);
63       var planeMaterial = new THREE.MeshBasicMaterial({
64         color: 0xcccccc,
65         wireframe: true
66       });
67
68       var plane = new THREE.Mesh(planeGeometry, planeMaterial);
69       plane.rotation.x = -0.5 * Math.PI;
70       plane.position.x = 0;
71       plane.position.y = smash.SphereSystem2.FLOOR_LEVEL;
72       plane.position.z = 0;

```

```

73     this.scene.add(plane);
75
76
77
78     var material = new THREE.MeshLambertMaterial({
79         color: 0xff0000
80     });
81 /**
82 * @type {!Array.<!THREE.SphereGeometry>}
83 */
84 this.threeSpheres = new Array(smash.SphereSystem2.SPHERES_COUNT);
85 for (var i = 0; i < smash.SphereSystem2.SPHERES_COUNT; i++) {
86     var sphere = new THREE.SphereGeometry(this.spheres[i].radius, 10, 10);
87     var mesh = new THREE.Mesh(sphere, material);
88     mesh.position.x = this.spheres[i].positionX;
89     mesh.position.y = this.spheres[i].positionY;
90     mesh.position.z = this.spheres[i].positionZ;
91     this.threeSpheres[i] = mesh;
92
93     this.scene.add(mesh);
94 }
95
96
97
98 /**
99 * @type {!THREE.WebGLRenderer}
100 */
101 this.renderer = new THREE.WebGLRenderer();
102 this.renderer.setSize(smash.SphereSystem2.CANVAS_WIDTH,
103                     smash.SphereSystem2.CANVAS_HEIGHT);
104 document.body.appendChild(this.renderer.domElement);
105 this.renderer.render(this.scene, this.camera);
106 }
107
108 /**
109 * @type {number}
110 */
111 this.collisions = 0;
112
113 /**
114 * @type {number}
115 */
116 this.collisionChecks = 0;
117
118 /**
119 * @type {smash.Octree}
120 * @private
121 */
122 this.octreeRoot_ = new smash.Octree(-1000, 1000, -1000, 1000,
123                                     -1000, 1000, smash.SphereSystem2.OCTREE_DEPTH);
124
125 for (var i = 0; i < smash.SphereSystem2.SPHERES_COUNT; i++) {
126     this.octreeRoot_.addSphere(this.spheres[i]);
127 }
128
129 if (smash.SphereSystem2.DRAWING_OCTREE_ENABLED) {

```

```
130  /**
131   * @type {Array}
132   * @private
133   */
134   this.octreeCubes_ = [];
135 }
136 };
137
138 /**
139 * @const {number}
140 */
142 smash.SphereSystem2.SPHERES_COUNT = 1000;
143
144
145 /**
146 * @const {boolean}
147 */
148 smash.SphereSystem2.DRAWING_ENABLED = false;
149
150
151 /**
152 * @const {boolean}
153 */
154 smash.SphereSystem2.DRAWING_OCTREE_ENABLED =
155     smash.SphereSystem2.DRAWING_ENABLED && true;
156
157
158 /**
159 * @const {number}
160 */
161 smash.SphereSystem2.OCTREE_DEPTH = 5;
162
163 /**
164 * @const {boolean}
165 */
166 smash.SphereSystem2.GRAVITY_ENABLED = true;
167
168
169 /**
170 * @const {number}
171 */
172 smash.SphereSystem2.GRAVITY_FORCE = 0.1;
173
174
175 /**
176 * @const {number}
177 */
178 smash.SphereSystem2.FLOOR_LEVEL = -100;
179
180
181 /**
182 * (1 - energy lost on floor hit)
183 * @const {number}
184 */
185 smash.SphereSystem2.FLOOR_FRICTION = 0.8;
186
```

```
187 /**
188 * @const {number}
189 */
190 smash.SphereSystem2.CANVAS_WIDTH = 1200;
191
192
193
194 /**
195 * @const {number}
196 */
197 smash.SphereSystem2.CANVAS_HEIGHT = 400;
198
199
200 /**
201 * @param {!smash.Sphere} sphere1
202 * @param {!smash.Sphere} sphere2
203 */
204 smash.SphereSystem2.collide = function(sphere1, sphere2) {
205   var sumVelocitiesLength = smash.math.vectorLength(
206     sphere1.velocityX, sphere1.velocityY, sphere1.velocityZ) +
207     smash.math.vectorLength(
208       sphere2.velocityX, sphere2.velocityY, sphere2.velocityZ);
209
210   var centerDiffX = sphere1.positionX - sphere2.positionX;
211   var centerDiffY = sphere1.positionY - sphere2.positionY;
212   var centerDiffZ = sphere1.positionZ - sphere2.positionZ;
213   var centerLength = smash.math.vectorLength(
214     centerDiffX, centerDiffY, centerDiffZ);
215   var velocityAdjust = centerLength * sumVelocitiesLength / 2;
216   centerDiffX /= velocityAdjust;
217   centerDiffY /= velocityAdjust;
218   centerDiffZ /= velocityAdjust;
219
220   sphere1.velocityX = centerDiffX;
221   sphere1.velocityY = centerDiffY;
222   sphere1.velocityZ = centerDiffZ;
223   sphere2.velocityX = centerDiffX * -1;
224   sphere2.velocityY = centerDiffY * -1;
225   sphere2.velocityZ = centerDiffZ * -1;
226 };
227
228
229 /**
230 * @param {!smash.Sphere} sphere
231 */
232 smash.SphereSystem2.prototype.applyGravity = function(sphere) {
233   if (smash.SphereSystem2.GRAVITY_ENABLED) {
234     sphere.velocityY -= smash.SphereSystem2.GRAVITY_FORCE;
235   }
236 };
237
238
239 /**
240 * @param {!smash.Sphere} sphere
241 */
242 smash.SphereSystem2.prototype.applyFloor = function(sphere) {
243   if (sphere.positionY - sphere.radius <
```

```

244     smash.SphereSystem2.FLOOR_LEVEL) {
245     sphere.velocityY *= -smash.SphereSystem2.FLOOR_FRICTION;
246   }
247 };
248
249
250 /**
251 *
252 */
253 smash.SphereSystem2.prototype.addOctreeMesh = function(node) {
254   if (!node.debugMesh) {
255     var width = node.right - node.left;
256     var height = node.bottom - node.top;
257     var depth = node.far - node.near;
258     var geom = new THREE.CubeGeometry(width, height, depth);
259     geom.applyMatrix(
260       new THREE.Matrix4().makeTranslation(
261         node.left + width/2,
262         node.top + height/2,
263         node.near + depth/2
264       )
265     );
266
267     node.debugMesh = new THREE.BoxHelper(new THREE.Mesh(geom));
268     this.octreeCubes_.push(node.debugMesh);
269
270     this.scene.add(node.debugMesh);
271   }
272
273   for (var i = 0; i < node.childNodes.length; i++) {
274     this.addOctreeMesh(node.childNodes[i]);
275   }
276 };
277
278
279 /**
280 *
281 */
282 smash.SphereSystem2.prototype.collideFromOctree_ = function(node) {
283   for (var i = 0; i < node.objects.length; i++) {
284     for (var j = 0; j < node.objects.length; j++) {
285       this.collisionChecks++;
286       if (i != j &&
287           smash.math.checkCollidingSpheres(
288             node.objects[i], node.objects[j])) {
289         this.collisions++;
290         smash.SphereSystem2.collide(
291           node.objects[i], node.objects[j]);
292       }
293     }
294   }
295   for (var i = 0; i < node.childNodes.length; i++) {
296     this.collideFromOctree_(node.childNodes[i]);
297   }
298 };
299
300 smash.SphereSystem2.prototype.stepOctree_ = function(node) {

```

```

301  var removedSpheres = [];
302  for (var i = 0; i < node.objects.length; i++) {
303    var sphere = node.objects[i];
304    if (node.sphereLeft(sphere)) {
305      node.removeSphere(sphere);
306      removedSpheres.push(sphere);
307    }
308  }
309
310 for (var i = 0; i < node.childNodes.length; i++) {
311   this.stepOctree_(node.childNodes[i]);
312 }
313
314 if (node !== this.octreeRoot_) {
315   for (var i = 0; i < removedSpheres.length; i++) {
316     this.octreeRoot_.addSphere(removedSpheres[i]);
317   }
318 }
319
320 if (!node.hasAnyObjects()) {
321   if (smash.SphereSystem2.DRAWING_OCTREE_ENABLED) {
322     for (var i = 0; i < node.childNodes.length; i++) {
323       this.scene.remove(node.childNodes[i].debugMesh);
324     }
325   }
326   node.childNodes.length = 0;
327 }
328 };
329
330
331 /**
332  *
333  */
334 smash.SphereSystem2.prototype.step = function() {
335   this.stepOctree_(this.octreeRoot_);
336   this.collideFromOctree_(this.octreeRoot_);
337
338   for (var i = 0; i < smash.SphereSystem2.SPHERES_COUNT; i++) {
339     this.applyGravity(this.spheres[i]);
340     this.applyFloor(this.spheres[i]);
341
342     this.spheres[i].step(1);
343
344     if (smash.SphereSystem2.DRAWING_ENABLED) {
345       this.threeSpheres[i].position.x = this.spheres[i].positionX;
346       this.threeSpheres[i].position.y = this.spheres[i].positionY;
347       this.threeSpheres[i].position.z = this.spheres[i].positionZ;
348     }
349   }
350 }
351
352 if (smash.SphereSystem2.DRAWING_OCTREE_ENABLED) {
353   this.addOctreeMesh(this.octreeRoot_);
354 }
355
356 if (smash.SphereSystem2.DRAWING_ENABLED) {
357   this.renderer.render(this.scene, this.camera);

```

```
358     }
359 }
```

Listing B.17: Octree-based sphere system object in JavaScript

```

1 /**
2 * @fileoverview Sphere collision detection system.
3 * @author sebastian.poreba@gmail.com (Sebastian Por  ba)
4 */
5
6 #include "sphereSystem2.h"
7
8 smash::SphereSystem2::SphereSystem2() {
9     this->spheres = new std::vector<smash::Sphere*>;
10    collisions = 0;
11    collisionChecks = 0;
12
13    octreeRoot = new smash::Octree(-1000, 1000, -1000, 1000,
14        -1000, 1000, smash::SphereSystem2::OCTREE_DEPTH);
15
16    float generalVelocity = 1;
17    for (int i = 0; i < smash::SphereSystem2::SPHERES_COUNT; i++) {
18        smash::Sphere* sphere = new smash::Sphere();
19        sphere->positionX = (((float) rand() / (RAND_MAX)) - 0.5) * 400;
20        sphere->positionY = (((float) rand() / (RAND_MAX)) - 0.5) * 200;
21        sphere->positionZ = (((float) rand() / (RAND_MAX)) - 0.5) * 100;
22        sphere->velocityX = (((float) rand() / (RAND_MAX)) - 0.5) * generalVelocity;
23        sphere->velocityY = (((float) rand() / (RAND_MAX)) - 0.5) * generalVelocity;
24        sphere->velocityZ = (((float) rand() / (RAND_MAX)) - 0.5) * generalVelocity;
25        this->spheres->push_back(sphere);
26        this->octreeRoot->addSphere(sphere);
27    }
28};
29
30
31 smash::SphereSystem2::~SphereSystem2() {
32     this->spheres->clear();
33     delete this->spheres;
34     delete this->octreeRoot;
35 };
36
37
38 /**
39 * @param {smash::Sphere*} sphere1
40 * @param {smash::Sphere*} sphere2
41 */
42 void smash::SphereSystem2::collide(smash::Sphere* sphere1, smash::Sphere* sphere2) {
43     float sumVelocitiesLength = smash::math::vectorLength(
44         sphere1->velocityX, sphere1->velocityY, sphere1->velocityZ) +
45         smash::math::vectorLength(
46             sphere2->velocityX, sphere2->velocityY, sphere2->velocityZ);
47
48     float centerDiffX = sphere1->positionX - sphere2->positionX;
49     float centerDiffY = sphere1->positionY - sphere2->positionY;
50     float centerDiffZ = sphere1->positionZ - sphere2->positionZ;
```

```

51     float centerLength = smash::math::vectorLength(
52         centerDiffX, centerDiffY, centerDiffZ);
53     float velocityAdjust = centerLength * sumVelocitiesLength / 2;
54     centerDiffX /= velocityAdjust;
55     centerDiffY /= velocityAdjust;
56     centerDiffZ /= velocityAdjust;
57
58     sphere1->velocityX = centerDiffX;
59     sphere1->velocityY = centerDiffY;
60     sphere1->velocityZ = centerDiffZ;
61     sphere2->velocityX = centerDiffX * -1;
62     sphere2->velocityY = centerDiffY * -1;
63     sphere2->velocityZ = centerDiffZ * -1;
64 };
65
66 void smash::SphereSystem2::applyGravity(smash::Sphere* sphere) {
67     if (smash::SphereSystem2::GRAVITY_ENABLED) {
68         sphere->velocityY -= smash::SphereSystem2::GRAVITY_FORCE;
69     }
70 };
71
72
73 void smash::SphereSystem2::applyFloor(smash::Sphere* sphere) {
74     if (sphere->positionY - sphere->radius <
75         smash::SphereSystem2::FLOOR_LEVEL) {
76         sphere->velocityY *= -smash::SphereSystem2::FLOOR_FRICTION;
77     }
78 };
79
80
81 void smash::SphereSystem2::collideFromOctree(smash::Octree *node) {
82     for (std::vector<smash::Sphere*>::iterator it = node->objects->begin(); it != node->objects->end();
83         for (std::vector<smash::Sphere*>::iterator it2 = node->objects->begin(); it2 != node->objects->end();
84             this->collisionChecks++;
85             smash::Sphere* s = *it;
86             smash::Sphere* s2 = *it2;
87             if (s != s2 &&
88                 smash::math::checkCollidingSpheres(s, s2)) {
89                 this->collisions++;
90                 smash::SphereSystem2::collide(s, s2);
91             }
92         }
93     }
94     for (std::vector<smash::Octree*>::iterator it = node->childNodes->begin(); it != node->childNodes->end();
95         this->collideFromOctree(*it);
96     }
97 };
98
99 void smash::SphereSystem2::stepOctree(smash::Octree *node) {
100    std::vector<smash::Sphere*> removedSpheres;
101
102    for (std::vector<smash::Sphere*>::iterator it = node->objects->begin(); it != node->objects->end();
103        smash::Sphere* s = *it;
104        if (node->sphereLeft(s)) {
105            removedSpheres.push_back(s);
106            it = node->objects->erase(it);
107            if (s == *it) {

```

```

108         break; // last element removal
109     }
110 }
111 }
112 }
113 for (std::vector<smash::Octree*>::iterator it = node->childNodes->begin(); it != node->childNodes->
114     this->stepOctree(*it);
115 }
116
117 if (node != this->octreeRoot) {
118     for (std::vector<smash::Sphere*>::iterator it = removedSpheres.begin(); it != removedSpheres.end();
119         this->octreeRoot->addSphere(*it);
120     }
121 }
122
123 if (!node->hasAnyObjects()) {
124     for (std::vector<smash::Octree*>::iterator it = node->childNodes->begin(); it != node->childNodes->
125         delete *it;
126     }
127     node->childNodes->clear();
128 }
129 };
130
131
132 void smash::SphereSystem2::step() {
133     this->stepOctree(this->octreeRoot);
134     this->collideFromOctree(this->octreeRoot);
135     for (std::vector<smash::Sphere*>::iterator it = this->spheres->begin(); it != this->spheres->end();
136         smash::Sphere* s = *it;
137         applyGravity(s);
138         applyFloor(s);
139         s->step(1);
140     }
141 };

```

Listing B.18: Octree-based sphere system in C++

Bibliografia