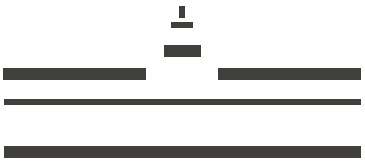

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Constructive Generation Methods for Dungeons

Seminar-Thesis in Procedural Content Generation for Games

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Declaration of Authorship

I hereby declare that, to the best of my knowledge and belief, this Seminar Thesis titled '*Constructive Generation Methods for Dungeons*' is my own work. I confirm that each significant contribution to and quotation in this thesis that originates from the work or works of others is indicated by proper use of citations and references.

Münster, June 30, 2015

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Abbreviations

ASM Attribute Similarity Measure

BNF Backus-Naur-Form

BSP Binary Space Partitioning

CA Cellular Automaton/Automata

CS Computer Sciences

ECA Evolving Cellular Automata

env. environment

FPS Frames Per Second

FV Fitness Value

GA Genetic Algorithm(s)

ms millisecond(s)

NPC Non-Player Character

PCG Procedural Content Generation

PCG-G Procedural Content Generation for Games

prev. Previous

RPG Role-Play Game

RTS Real-Time Strategy

Symbols

number of/count

1 Introduction

Chances are high, that most people who will read this will have played some kind of a video game; be it the retro games back in the 1980s and 90s when computer games became popular or one of the more up-to-date mobile games.
However chances are probably equally high, that terms like *Procedural Content Generation* (PCG) or *Constructive Generation Methods* are unknown to the very same reader. And the justified question at this point could be:

> *Why should anyone actually care about it?*
> → Because **PCG** could very well be the **next Big Thing** in the gaming sector!

And this holds true for both - those who are 'just' playing them, but also for those who are more interested in creating them. For those who belong to the group not yet convinced by this answer, the Definitions section - and there especially the part concerning motivation - will be a good start to get a better insight. Just to foreshadow some bits: While the idea of '*Time being money*' will be proven again, the idea that '*Everything has an end*' will possibly be one to question after reading the thesis.

> *But why dungeons?*
> → As they are one of the **PCG origins** and still a **popular element** of many RPGs and FPS.

Those who not already fought through a virtual dungeon could have a look at the part concerning Dungeons to get a better idea of what this is all about.
Another part of the answer of course is, that this seminar thesis only has limited space whereas the research area of PCG is already pretty large. And as some preliminary research in the '*PCG Book*' by Togelius et al. (2015b) revealed some intersting algorithmic solutions in the area of dungeon generation, the decision was made to write this thesis in exactly this area.
Finally three algorithms (*Space Partitioning, Cellular Automata and Generative Grammars*) and one extension (*Evolving Cellular Automata*) were chosen to be discussed in more detail in the main part of this paper.
So for everyone who is now eager to get deeper into the topic, the answer to the final question:

> *And where are the algorithms?*
> → Right here: Constructive Generation Methods for Dungeons.

Having read the complete thesis a reader should have a basic understanding of the discussed algorithms, their strenghts and downsides. Furthermore it should become clear, that there is no single truth in creating dungeons and that most algorithms can be improved, e.g. by combining them with others.

2 Definitions

After already having talked about some topic-specific terms/ideas in the introductory section, it might be helpful to discuss and define some of the terms. This shall help to establish a common understanding for this thesis, but also enable readers with no or no strong background in this thematic setup to get straight up into the topic.

2.1 Procedural Content Generation (for Games)

As this thesis is settled in the research area of Procedural Content Generation (PCG), it makes sense to get a definition for this subject first.
Being no particularly young research field, dating back to 1980 when *Rogue*, the first game employing PCG mechanisms (Khaled et al. 2013) was published, it seems that PCG is only receiving larger scientific interest for the last 10 years, when own journals and conferences where established (ACM 2015; IEEE 2015; Bidarra et al. 2010).
This may be one reason, that - instead of one consolidated one - there still is a range from rather abstract definitions like the Gamasutra (2012) one

> *The platonic Procedural Content Generation algorithm allows you to create entire universes by pressing a button.*

to more concrete and precise ones like the one Togelius et al. (2015a) use in their yet unpublished PCG-Book:

> *The definition we will use is that PCG as the algorithmical creation of game content with limited or indirect user input.*

Here it is interesting to note, that some authors (e.g. Hendrikx et al. (2013)) use the term Procedural Content Generation for Games (PCG-G) rather than just PCG - probably to clearly separate it from approaches using PCG for art creation (Wikidot 2009) or movie creation (Massive 2011). Yet most papers and sources tend to simply use PCG synonymously to PCG-G, so this thesis will follow this pattern.
What can be derived from both above cited (and also other) definitions is, that the overall aim of PCG is to go away from manually generating game content, towards an automated/procedural approach based on algorithms - or to make it short: a mostly[1] computer-based instead-of human based content generation. A real-world example according to Togelius et al. (2015a) could be a tool, that generates dungeons for a game like *The Legend of Zelda* without human interaction, whereas map editors where a player can create RTS game maps would not be considered a PCG tool.

[1] mostly, as for example Togelius et al. (2015b) and others propose so called *mixed-initiative approaches* where computers and humans co-create content

To make the topic a little more quantifiable/tangible Togelius et al. (2015a) propose the following five desirable properties when discussing PCG solutions (as we are going to do in the course of this thesis):

Speed	Reliability	Controllability	Expressivity and diversity	Creativity and believability
having content in time	having content in a desired quality	human can specify certain aspects	diverse set of content	content should not look 'generated'

Table 1: Five desirable PCG properties

2.1.1 Content

Since it is the outcome of PCG efforts, as a next step it is helpful to get a better idea of what is subsumed under the term *content*.
In their paper on 'Search-Based Procedural Content Generation' Togelius et al. (2011) (also taken up in the upcoming PCG Book (Togelius et al. 2015a)) defined (game) content as

> *content [that] refers to all aspects of the game that affect gameplay other than nonplayer character (NPC) behaviour and the game engine itself*

where they consider these aspects to be things like terrain, maps, levels, stories etc.
A somewhat different[2] yet more extensive approach is taken by (Hendrikx et al. 2013) in their survey on PCG for games. They provide a six-class taxonomy of procedurally generatable game content which allows further insights into what content is, but also indicates that content is a rather multi- then single-dimensional idea:

Game Bits	Game Space	Game Systems	Game Scenarios	Game Design	Derived Content
textures	indoor maps	ecosystems	puzzles	System Design	News and Broadcasts
sound	outdoor maps	road networks	storyboards	World Design	Leaderboards
vegetation	bodies of water	urban env.	story		
buildings		entity behaviour	levels		
behaviour					
fire, water, stone, clouds					

Table 2: Six classes of game content (Hendrikx et al. 2013)

In this thesis multiple classes will be - at least partly - covered: this includes *Game Space* (outdoor and indoor maps), *Game Scenarios* (Levels), *Game Design* (System Design) and implicitly *Game Bits*. Why these types of content matter for the constructive generation of dungeons will hopefully become clear in the following sections.

[2] the difference is, that Hendrikx et al. (2013) regard NPCs as part of PCG whereas e.g. Togelius et al. (2015a) argue it is not - but as this is no concern of this thesis there will be no further elaboration on this fact

2.1.2 Games

Talking about games in the PCG context does - in contrast to what one might think regarding the previous sections and the literature often coming from a CS background (e.g. see the references of this paper) - not only include computer games, but can as well mean board games, card games and puzzles (Togelius et al. 2015a). For this thesis however, the range will be limited to computer games, as the setting for the dungeons to be created[3].
When it comes to formally defining the term *Games* there is some conflict, as for example Salen and Zimmerman (2003)[4] point out the difficulties to define the term, but yet provide a definition (that for example Browne and Maire (2010) take up), whereas e.g. Togelius et al. (2015a) reject the idea to define the word completely. Yet all of them propose some key elements of games:

Togelius et al. (2015a)	Browne and Maire (2010)	Salen and Zimmerman (2003)
design	rules/means	system
affordances	play	players
constraints	outcome/ends	artificial
playable		conflict
		rules
		quantifiable outcomes

Table 3: Key elements of games

So it can be stated that a *Game* somehow involves playing under certain conditions/rules and must lead to a certain end with a certain outcome.

2.2 Dungeon

While the original definition of a dungeon, as e.g. given by the Oxford Dictionary (2015), refers to an underground prison cell, the definition for dungeons in games is less restrictive characterizing

> *adventure and RPG dungeon levels as labyrinthic environments [(rooms connected by hallways)], consisting mostly of inter-related challenges, rewards and puzzles, tightly paced in time and space to offer highly structured gameplay progressions*

that can include additional elements like characters (NPCs), decorations etc. (Shaker et al. 2015). As a distinguising characteristic of dungeon levels van der Linden et al. (2013) identified the '*close control over gameplay pacing*' respectively the '*tighter bond between designing gameplay and game space*'. To illustrate this idea one can build on the proposed comparison to open world games or platform games (van der Linden et al. 2013): So for example in race track game (*platform game*) there will usually a predefined track without much variation (as in it's real world pendant), whereas in an open-world games like GTA V the player can freely explore the world. In a dungeon game however, the player may encounter something like a main track/hallway, that leads to an end boss

[3] even though there are also board games based on dungeons available (*Dungeon!*; Wizards of the Coast 2015) that according to Shaker et al. (2015) are predecessors of the modern computer versions

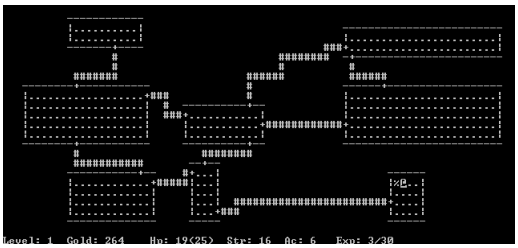
[4] the definition can be found in Salen and Zimmerman (2003, p.11) - the underlying definitions can be found in Salen and Zimmerman (2003, p.4-9)

or a treasure, which has multiple rooms and/or hallways diverging from it - so there is control as the player will have to follow the main path, but also exploration as there is no prescribed way to explore the other areas of the dungeon.
Known examples for games employing dungeons are *Diablo*, *Rogue*, *Doom*, *Half Life*, *Sacred* etc. (Adams 2002; van der Linden et al. 2013). Screenshots (Figures 1a-1d) from some of those games can be found on the next page and maybe help to get a better visual impression of what a 'real virtual' dungeon looks like.

2.3 Motivation

So before finally starting with the main part, the last remaining question may be, why the whole topic is relevant.
One reason is the growing complexity of games[5] (Hendrikx et al. 2013) in combination with the rising number of people playing games (Hughes 2012; BITKOM 2014) (statistics regarding Germany see: Appendix A), both creating a rising demand for more and more content. The resulting growth in numbers of content designers from single persons per game to hundreds (Hendrikx et al. 2013) resulted in rapidly growing expenditures for content generation[6]. This and also the lack of scalability (Iosup 2011) and timeliness (Kelly and McCabe 2007) made PCG a candidate to either reduce artists or at least increase their efficiency (Togelius et al. 2015a).
Furthermore real-time PCG instead of manual content generation can help to automatically adjust difficult levels (Togelius et al. 2015a), so that gamers would always be challenged at their current level. Also games like Super Tux would not have to end after a fixed amount of levels, as theoretically at the end of each level a new one could be generated (Togelius et al. 2015a; Supertux.lethargik.org 2014).
The last advantage Togelius et al. (2015a) see, is that a PCG approach, e.g. for dungeon or level generation, could potentially create dungeons and levels that a human designer might not even think of and thus offer completely new experiences.
That is plenty of reasons to now have a closer look at algorithms and methods to understand what is the current state of the art, and where there is still limits.

[5] Hendrikx et al. (2013) found evidence that already in 2008 the game *World of Warcraft* contained about 30.000 items, 5300 interactable creatures etc.
[6] if the evidence Hendrikx et al. (2013) found is correct, and about 40% of game cost is for content, e.g. for modern blockbuster productions like GTA 5 the content cost would be about 106 million dollar (McLaughlin 2013)



(a) Rogue

(b) Diablo II

(c) Sacred

(d) Doom

Figure 1: Dungeon-Screenshots from different games
Source: (Venator_Noctis 2011; Valencia 2006; Willbr 2006; Artoftransformation 2008)

3 Constructive Generation Methods for Dungeons

In the main section of this thesis, it will be the aim to discuss a selected set out of the variety of methods to procedurally generated dungeons.
While Shaker et al. (2015) and van der Linden et al. (2013) typically distinguish three steps to make up a dungeon generation method, most of the following methods will focus on the *representational model*[7] as well as the *method to construct that representational model*. The translation into the actual dungeon will not be a central aspect.
Another limit that should be mentioned beforehand is the large focus on 2D games - so what van der Linden et al. (2013) state regarding genetic algorithms (*'may allow some form of 3D mapping, the current work only focuses on 2D'*) holds true for most of the other presented approaches.

3.1 Space Partitioning

To allow a more or less easy entry into dungeon map/level PCG, space partitioning was chosen as a first method.

3.1.1 Areas of Application, Pros and Cons

This is based on the fact, that Shaker and Liapis (2013) and Pedersen (2014a) categorize this method as an easy to implement, relatively simple approach. It would be the recommended way to go, whenever the aim is the creation of a rather structured, neatly aligned dungeon, without overlapping rooms. So recalling the desirable PCG properties (see Table 1) one can say that at least in terms of *diversity* and *believability* the structuredness might be a problem - simply because natural cave like dungeons could not be generated by Space Partitioning, but rather only 'man-made' dungeon structures (like 'real' dungeons). And even there too much symmetry might create a feeling of generated content[8], so those two points make clear, why the structuredness is one of the downsides of the space partitioning approach.
Another downside has been found by Williams (2014) regarding the lack of control e.g. over the number of rooms (reasons see algorithmic description in section 3.1.3), which would violate the *controllability* property.
To allow a better overview over Pros and Cons they are summed up in Table 4.

Pro	Contra
easy implementation/simple	very neat/organized
no overlaps	looks 'generated'
easy creation of groups of rooms	very limited control

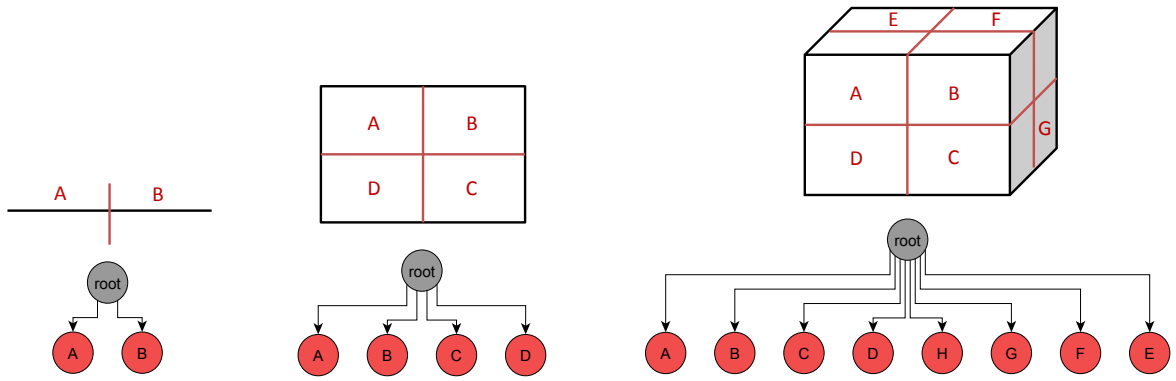
Table 4: Advantages and Disadvantages of Space Partitioning
Source: (Shaker et al. 2015; Shaker and Liapis 2013; Williams 2014)

[7] to have an arbitrary example of such a model, one could just imagine treating a dungeon as an array of 0 and 1 to distinguish between wall and stone

[8] a quote illustrating that notion would be '*There are no straight lines or sharp corners in nature. Therefore, buildings must have no straight lines or sharp corners.*' (*Antoni Gaudí*)

3.1.2 Background Information

This paragraph will give some details about the theoretical background of this method before its application for dungeon generation will be illustrated.
The basic idea behind the space partitioning algorithm is taking a given 2D/3D-space[9] and dividing it into disjoint[10] subsets - typically hierarchically with a recursive algorithm (Shaker et al. 2015). As a data-structure usually a tree is used to represent the subsets and their hierarchy - also called *space-partitioning tree* (Shaker et al. 2015).
For the dungeon-creation the special form of *binary space partitioning* (BSP) - a technique originally developed to efficiently display computer graphics around 1980 (Toth 2005; Fuchs et al. 1980)[11] - can be used (Shaker et al. 2015). The BSP method will be used to recursively split a (2D) space in halves until a certain level of granularity is reached[12] - here it has to be noted, that the partitions do not need to be of equal size, but can be defined by custom rules (Shaker et al. 2015). This can be visualized by the so called BSP tree, a binary tree like in Figure 2a just with the difference, that it operates on a 2D space like the Quadtree in 2b. So the overall idea of Figure 2 is to show, that BSP has multiple variants to treat different dimensions and that the Quadtree would be a potential alternative to traverse the 2D space, whereas the Octree could be used for 3D space (Shaker et al. 2015).



(a) Binary Tree **(b)** Quadtree **(c)** Octree

Figure 2: Different Tree Types for different dimensions

[9] This all-encompassing view of the dungeon right from the start is the reason, why this approach is also called a *macro* approach (Shaker et al. 2015).
[10] subsets being disjoint is the reason why no overlaps can exist in BSP - because by the definition of *disjoint* no piece of space can be stored twice within the tree and can thus not be used twice
[11] one game where BSP for graphics was used is DOOM - here David Fetter developed a project that displays this system (see: `https://www.youtube.com/watch?v=e0W65ScZmQw`)
[12] the level of granularity may vary depending on the context - but e.g. for a dungeon rooms with the size of one pixel would make no sense - thus breaking a given space down to that level is not necessary

3.1.3 Dungeon Creation Algorithm

The following algorithm finally describes the generation of a dungeon level and is based on the algorithmic descriptions of Shaker et al. (2015) and Williams (2014) and can - with small deviations - be seen in implemented form in Simon (2009) and Hely (2013).

Code-Lines 1-6 in Listing 1 and Images 3a to 3d

As one might asume at this position, the previously (see section 3.1.2) introduced BSP method will be used to divide a given dungeon space into smaller subsets, that can then be filled with rooms. The decision in which direction a section will be split can e.g. be random (Shaker et al. 2015) or be biased by given cell-sizes (Simon 2009) - the only limiting factor in that regard isb that the resulting subsets must still have a certain size[13] (e.g. not less than either a quarter of the original width or height).

Code-Lines 7-8 in Listing 1 and Image 3e

Once subdividing of the dungeon area is finished, the leaf nodes representing the dungeon structure have to be filled with rooms. Shaker et al. (2015), Simon (2009), and Hely (2013) propose drawing rectangles within the partition, underlining the importance of having rooms smaller than the partition itself and being 'in' the partition to prevent connected rooms[14]. To add more variation, Williams (2014) proposes to only randomly place rooms in partitions or to use handmade tiles or procedurally generated shapes as rooms instead of simple rectangles.

Code-Lines 9-10 in Listing 1 and Images 3f to 3h

To satisfy the game requirement of being playable (see Games) in a final step the rooms have to be connected. Here random methods to connect different rooms are possible (Williams 2014) but the BSP tree can be used again: By connecting rooms sharing the same parent node (*siblings*) from the leaves to the top, all rooms will be connected and on top of that, intersections of corridors with other corridors and rooms will be prevented (Shaker et al. 2015; Williams 2014).

```
1  start with the entire dungeon area  // root node of the BSP tree
2  divide the area along a horizontal or vertical line
3  select one of the two new partition cells
4  if this cell is bigger than the minimal aceptable size:
5    go to step 2  // using this cell as the area to be divided
6  select the other partition cell, and go to step 4
7  for every partition cell:
8    create a room within the cell by randomly choosing two points ("top left
       and bottom right") within its boundaries
9  starting from the lowest layers, draw corridors to connect rooms in the
     nodes of the BSP tree with children of the same parent
10 repeat 9 until the children of the root node are connected
```

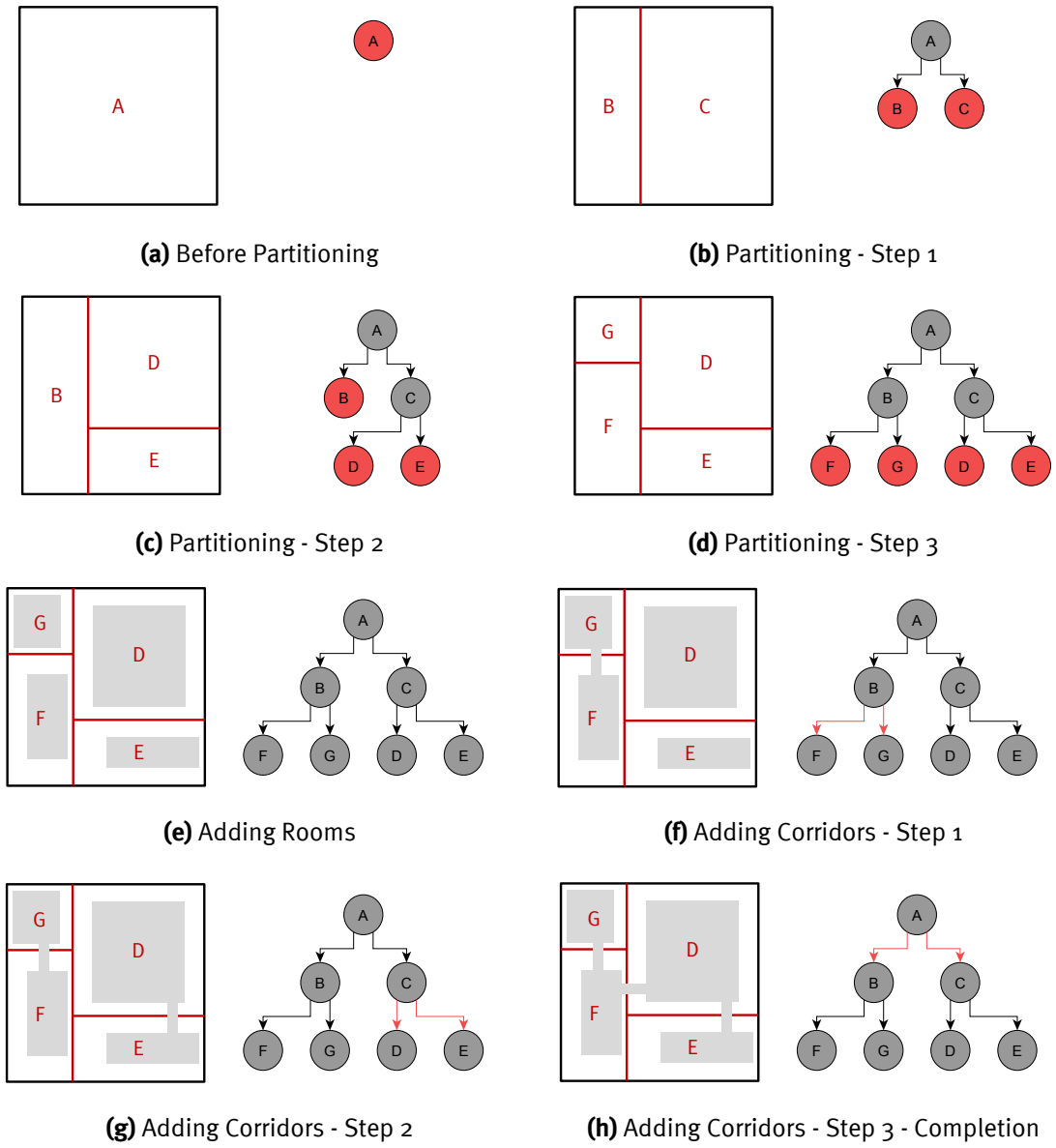
Listing 1: BSP Algorithm for Dungeon Generation - Source: (Shaker et al. 2015)

[13] this is the reason for the lack of controllability - because due to the random splits it is not clear how many of them happen before the constraint is reached (and as splits create the spaces for rooms the room number depends on the number of splits)

[14] the connection between rooms would come to pass, if in two neighboring cells the rooms would be placed exactely on the border of those two cells

Add on

Even if not represented in Listing 1, one could continue the dungeon creation by adding decorations to the dungeon (enriching the *Game Space* with *Game Bits*) to increase both *diversity* and *believability* of the dungeon. Again the BSP tree can be used, e.g. to define thematic areas[15] (Shaker et al. 2015) or to ensure '*playable*' placement of keys[16] or other elements (Williams 2014).



(a) Before Partitioning

(b) Partitioning - Step 1

(c) Partitioning - Step 2

(d) Partitioning - Step 3

(e) Adding Rooms

(f) Adding Corridors - Step 1

(g) Adding Corridors - Step 2

(h) Adding Corridors - Step 3 - Completion

Figure 3: BSP Dungeon Generation Algorithm

[15] Shaker et al. (2015) points out due to the BSP tree hierarchy, there will typically only be one entrance to the rooms represented by the child nodes of one non-leaf node in the tree - so for each non-leaf node a multi-room thematic area can be created

[16] Williams (2014) proposes e.g. placing a key the child nodes of the node with the corresponding door

3.2 Cellular Automata

After discussing the Space Partitioning method used to generate very structured and symmetric dungeons, the next step will be to have a look at an approach capable to generate more natural looking dungeons - the *Cellular Automaton*.

3.2.1 Areas of Application, Pros and Cons

This already forestalled a potential area of application as well as the first advantage of this method. While, as has been discussed in the previous parts, the Space Partitioning method could be used to generate dungeons that look human made, the Cellular Automaton can be useful to generate more 'natural'/organic looking caverns (Shaker et al. 2015; Anonymous 2014; van der Linden et al. 2013). In terms of *diversity* and *believability* this can be seen as an advantage.
Shaker et al. (2015) also underline the versatility of CA (potential areas of application see: Gibson et al. (2013, p. 12)) as well as their ability to generate infinite dungeon levels[17] and this even online/while the game is being played. To prove the efficiency, Johnson et al. (2010) - the CA for PCG algorithm developers - tested it and reported the low average generation time of $4.1 \cdot 10^{-1}$ milliseconds ($\approx$ 0.06 FPS), even with a from today's point of view slow computer with a 1.73 GHz single-core CPU[18].
Another implicitly mentioned pro-argument is the theoretically higher control with four (respectively five) variables (see section 3.2.3) - yet this is also one of the contra arguments, as van der Linden et al. (2013) and Shaker et al. (2015) argue, that the parameters exist, but due to interaction effects the influence of a single one is hard to predict. This makes it difficult to adjust the game to any specific technical or gameplay requirements other than by trial and error (Shaker et al. 2015).
Moreover van der Linden et al. (2013) and Johnson et al. (2010) are concerned that the CA method as proposed by Johnson et al. (2010) is only viable for 2D but not 3D both for reasons of control as well as playability. To illustrate it one can imagine a simple path in a 2D space - if it is free it is free - yet in 3D the same 2D path could exist and yet special procedures/rules would be needed to ensure that the path also has a 'walkable' height to be passable (see Figure 4).
As a last issue Anonymous (2014) mentions problems with larger maps not looking very well, but only provide indirect proof by mentioning issues with non-connected caverns in the dungeon, respecitively larger free areas.
For a better overview, the arguments for and against the Cellular Automata are compiled into a small table (Table 5) like in the Space Partitioning section.

[17] meaning that a given player could move in every direction in a dungeon, without ever reaching an end
[18] yet in another section of his article he reports a generation time of 349 ms for another CA map - which today would most likely not be seen as real time as for example gamers complain about a game being unplayble if their latency goes over 300 ms (as a comparison), cf. I_2_i et al. (2010)

Pro	Contra
versatile	impact of parameters often unclear
not looking generated	no requirement specific adjustments
fast/low computational cost	connection to gameplay is trial & error
control (*4 Parameters*)	more control issues when in 3D
infinite dungeons possible	difficulties for larger maps

Table 5: Advantages and Disadvantages of Cellular Automatons
Source: (Shaker et al. 2015; Johnson et al. 2010; van der Linden et al. 2013; Anonymous 2014)

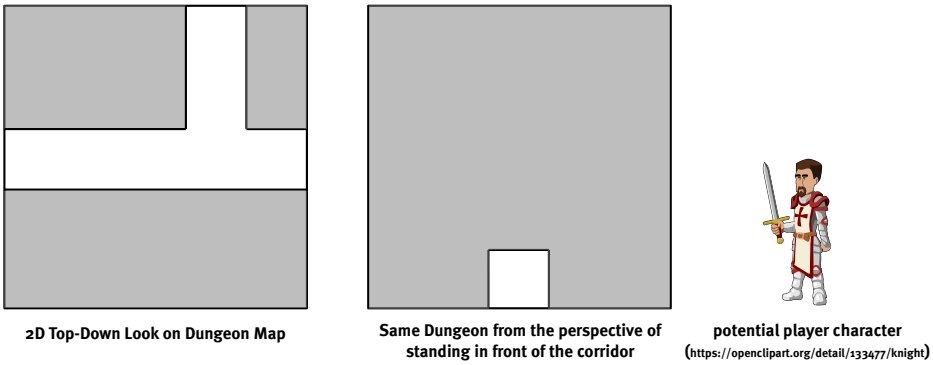


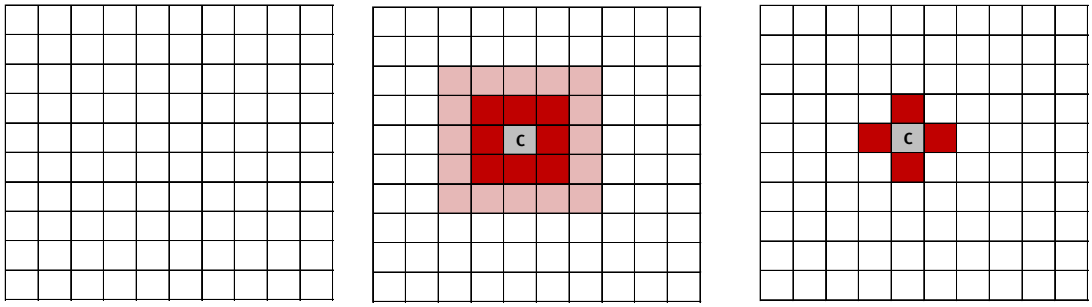
Figure 4: 3D-Dungeon Generation Issue

3.2.2 Background Information

The idea behind the CA is not new, as the first ideas and papers in that direction where published around 1950 by John von Neumann and Stanislaw Ulam (Wolfram 2002). Since then CA have been used in many science areas (*biology, physics*, ...) (Gibson et al. 2013) leading to a large amount of research regarding CA. So here only a short overview over the most important aspects will be provided.
The very basic element the CA will operate on, is a 2D grid of cells (Figure 5a) (other dimensionalities possible but uncommon) with each of the cells being in a finite amount of states (something like $\{0, 1\}, \{wall, path\}, \{gray, red\}$) (Shaker et al. 2015; van der Linden et al. 2013).
Another characteristic of this method is the concept of so called *neighbourhoods*, which refers to the cells surrounding a chosen cell (van der Linden et al. 2013). Two common patterns are the *Moore* and the *von Neumann* neighbourhood (more exist, e.g. for reference Tyler (1970)[19]):

- the *Moore* neighbourhood (Figure 5b) spans all cells (marked in dark red) surrounding a selected cell (marked in gray) - it can even have multiple levels (second level indicated in light red) (Shaker et al. 2015)
- the *von Neumann* neighbourhood (Figure 5c) only includes the cells in the north, south, west and east of the selected cell (Shaker et al. 2015)

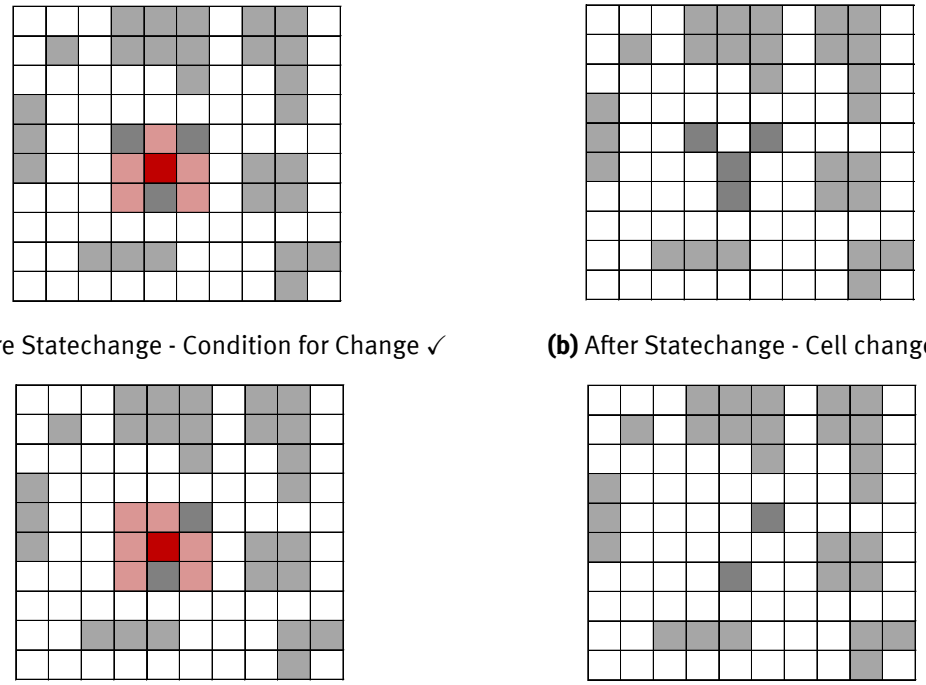
[19] 1970 is not the publication data of that web-page - unfortunately this date had to be used as a placeholder as the used citation tool does not support empty areas for the year and with no year LaTeX would use the website title in brackets which looks rather bad



(a) 10×10 CA Grid **(b)** Moore Neighbourhood **(c)** von Neumann Neighbourhood

Figure 5: Grid and Neighbourhoods of Cellular Automata

As CA are time-discrete systems (Shaker et al. 2015), they change their state in time-steps and not continuously (so a sequence like $t_0 \rightarrow t_1 \rightarrow ... \rightarrow t_n$ exists).
The type of the state change is determined by a fixed set of rules and the given neighbourhood and usually all cells change their state after a time step (Shaker et al. 2015; Pedersen 2014b). So there could be the simple rule in a dungeon level, that whenever there are three cells of wall in the neighbourhood of a cell, it will be transformed to a wall as well (or to a path if there is less than three wall cells and the cell is a wall). The cell's state in time t_n would then be based on the sum of wall-cells in it's neighbourhood in t_{n-1} and it's own state in t_{n-1} (Shaker et al. 2015).
The statechange process is visualized in Figure 6, where gray cells represent wall, the dark red cell the currently selected cell and the lightred cells are supposed to indicate a Moore neighbourhood.



(a) Before Statechange - Condition for Change ✓ **(b)** After Statechange - Cell changed

(c) Before Statechange - Condition for Change × **(d)** After Statechange - Cell not changed

Figure 6: Statechange in CA with a Moore neighbourhood of level 1

3.2.3 Dungeon Creation Algorithm

The preceeding section already introduced a lot concepts that make up the Cellular Automaton Dungeon Creation Algorithm, as it is proposed by Johnson et al. (2010). So this section will focus on the topics not yet discussed, that are needed to successfully generate a dungeon.
At first that will concern the parameter- and rule-set that is used to steer the CA. Table 6 introduces the shortcuts, a short description and proposed values:

Variable	Description	Example
r	initial percentage of rock cells	0.5 (50%)
n	CA iterations	2
T	neighbourhood value[20]threshold that defines a rock	5
M	Moore neighbourhood size	1

Table 6: Cellular Automata Steering Variables - Source: Johnson et al. (2010)

Given the knowledge of the previous section a fifth variable - the type of the neighbourhood - could be discussed, but is neglected for the current approach.
The only rule Johnson et al. (2010) use is close to the one used e.g. in Figure 6:

- $T = 5$ with the meaning, that if in the neighbourhood of a cell there is five rock cells it is converted to rock - elsewise it will be converted to a floor cell

Codelines 1-8 in Listing 2
In the first half of the algorithm should not be too many surprises, as it in large parts resembles the general work pattern of a CA discussed in the previous part - it starts with the initilzation of the grid in a certain size and the conversion of r (or here 50%) of the cells to rock with uniformly distributed random numbers. Afterwards the automaton runs $n = 2$ times, calculating the neighbourhood value and converting cells depending on the value being bigger or smaller $T = 5$.
Codelines 9-10 in Listing 2
To ensure that a player can continuously play it is important, that once he reaches the end of a grid he can directly advance to the next. This is achieved by not only generating the so called *base grid* (codelines 1-8), but also generating the adjacent grids of it in the same step (Johnson et al. 2010). Again it can be discussed how the neighbourhood is defined, as Johnson et al. (2010) for adjacent grids proposes a von Neumann neighbourhood, Shaker et al. (2015) a Moore neighbourhood.
So basically the code steps 1-8 are then applied to the neighbouring 4 respectively 8 grids to set up the dungeon structure there as well (Johnson et al. 2010). In a somewhat reduced[21] version this procedure will be run repeatedly throughout the game, as every time the player enters a new grid, its neighbours have to be generated (Johnson et al. 2010).

[20] the neighbourhood value is the number of rock cells in a given neighbourhood, so e.g. in a Moore Level 1 neighbourhood this value will lie between 0 and 9
[21] reduced as depending on the neighbourhood not each neighbour will have to be generated as some already exist

Codelines 11-12 in Listing 2

After this step is completed, there is five respectively nine dungeon-grids, yet it is not sure that those are connected (Johnson et al. 2010). If no connection can be found, Johnson et al. (2010) propose to establish it by picking the two floor cells closest to the border of two grids and digging a tunnel between them. This ensures the overall *playability* of a level (see Games).

Codelines 13-14 in Listing 2

Upon completion of the previous steps theoretically a playable dungeon would be available to the player. However, as the each grid was generated by a separate CA run and tunnels were dug in a straight line, the *believability* may have suffered, as the dungeon may be rather inconsistent in design (Johnson et al. 2010). The proposed solution are another n CA runs on the whole dungeon (all five/nine grids) to remove the given flaws (Johnson et al. 2010).

Codeline 15 in Listing 2

This last step in the algorithm is necessary to ensure that a player can actually return to a location in a dungeon and will encounter the same 'setting', as has been there before (Johnson et al. 2010). To achieve this, an implemention of the algorithm will have to store the seed for the base grid including pointers to neighbouring grids (Johnson et al. 2010) (which then will be in need to be updated on expansion of the dungeon due to player exploration).

Add on in Listing 3

Having used a CA to create a mobile app, Pedersen (2014b) observed a problem that Johnson et al. (2010) do not adress in their paper explictetly: within a grid the CA might generate lots of different caverns, which are not necessarily connected.

This is why he proposes to use the illustrated flood fill algorithm to identify the different caverns (Pedersen 2014b). The first lines of the code (1-5) are used to traverse the whole grid, meaning that each cell that is a path cell and not already 'filled' with a `fillNumber`, will be the starting point of a new cavern with a new `fillNumber`.

For this new cavern a `floodFill(fillNumber)`-operation is called, that will set a cell to a given `fillNumber` whenever it is no rock and recursively invoke itself for all it's neighbouring cells (here a von Neumann neighbourhood was chosen)[22]. At a certain point the recursion will stop, as it will only hit cells that are either filled or rock cells - then control goes back to the steering function described in codelines 1-5. To not overwrite the grid, the flood fill will be done with a copy of the original grid structure (Pedersen 2014b).

Having identified the caverns Pedersen (2014b) considers two ideas worth implementing:

- filling all but the largest cavern to keep the natural dungeon look, but with the issue of loosing playable area[23]
- connecting the caverns with the downside of having straight tunnels between caverns[24]

[22] an animation illustrating the process can be found at `http://cdn3.raywenderlich.com/wp-content/uploads/2014/02/Flood-Fill.gif`

[23] Anonymous (2014) chose a comparable flood fill approach and to solve the problem of loosing area the dungeon was recreated when the remaining path/floor area was below a certain threshold like 45% of the dungeon

[24] whereas when integrated into Johnson's algorithm depending on its placement the new tunnels would also be subject to a rerun of the CA like the tunnels between grids, which would solve this problem

```
initialize empty grid with a x b cells  // e.g. 50 x 50
initialize floor cells
  convert randomly with probability r
for n iterations
  go through each cell
    calculate neighbourhood values
    if past threshold T
      convert
create adjacent grids // for square cells that will be 4 or 8
  for each repeat steps 1-8
if two adjacent grids are not connected
  create a connection // between two accessible areas
run n additional CA iterations  // removing inconsistencies
create wall cells // special rock cells
store base grid and pointer to adjacent grids // allows restoring the grid
```

Listing 2: CA Algorithm for Dungeon Generation - Source: (Johnson et al. 2010)

```
//  Function to iterate through all cells
for each cell
  if not already filled and a path cell
    floodFill(fillNumber)
    increase fillNumber

//  floodFill-Function to fill a cavern with a number to identify it
if cell is not of type floor/path
  return
set cell to fillNumber
go recursively through neighbour cells
  floodFill(fillNumber) for northern cell
  floodFill(fillNumber) for eastern cell
  floodFill(fillNumber) for southern cell
  floodFill(fillNumber) for western cell
```

Listing 3: CA Flood Fill Cavern Identification - Source: (Pedersen 2014b)

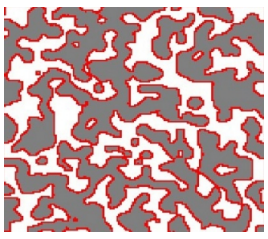


Figure 7: CA Dungeon
Source: (Johnson et al. 2010)

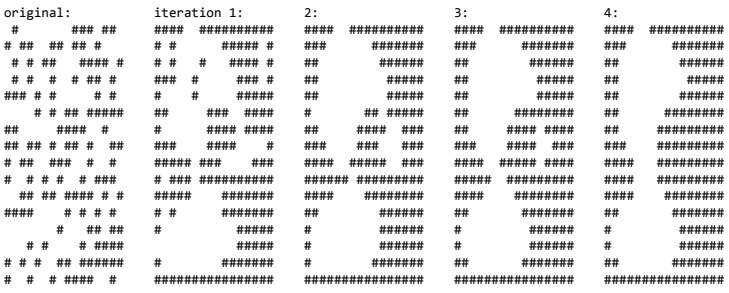


Figure 8: CA Dungeon Creation Process Schema
Source: (Anonymous 2014)

3.3 Evolving Cellular Automata

The *Evolving Cellular Automata* as recently proposed by Pech et al. (2015) uses Genetic Algorithms (GA) to improve CA for dungeon/maze generation.

3.3.1 Areas of Application, Pros and Cons

The area of application and most of the Pros and Cons are basically equal to those discussed for the Cellular Automata. This is the case, as this approach again uses a CA to generate dungeons (Pech et al. 2015), which naturally will enjoy the same benefits like other CA, including the organic and 'realistic' look, as well as being fast and easy to compute at the same time.
As already indicated above, the major difference in terms of advantages is, that the Evolving CA (ECA) does not suffer from the difficulties of manual rule creation, but uses a GA to evolve the rules automatically (Pech et al. 2015). For completeness it should be mentioned, that Genetic Algorithms themselves are an option to generate dungeons[25] and are combined with CA, as they generate proper levels but lack real-time capability, taking up to 20 minutes per dungeon (Pech et al. 2015). Yet even this algorithm has downsides when used: As it will use pre-generated mazes/dungeons[26] and versions that have been modified by a CA (see Dungeon Creation Algorithm) to evaluate the CA (ruleset), it depends on a reasonable selection of attributes to judge whether two mazes/dungeons have a comparable style (Pech et al. 2015).

Pro	Contra
advantages of a normal CA	difficult to specify attributes capturing visual style
no difficult manual rule creation	

Table 7: Advantages and Disadvantages of Evolving Cellular Automata
Source: (Pech et al. 2015)

3.3.2 Overview over Genetic Algorithms

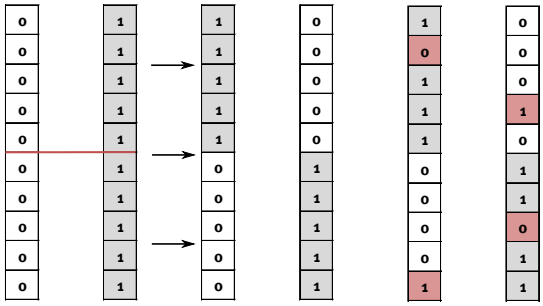
As GA are not covered in more detail in this thesis, this part shall provide a brief overview (more detailed introductions covering more variations e.g. in de Weck and Wilcox (2010) and Weise (2009)). The GA as a subclass of the evolutionary algorithms (Weise 2009) try to computionally simulate the natural/biological genetic evolution. To do this, the basic unit is the so called *chromosome* or *gene*, which typically is a fixed-/variable-length tuple (Weise 2009) of integers, characters or even colors (de Weck and Wilcox 2010)[27] (examples, e.g. Fig. 9a). A number of these chromosomes, the so called *population*, is then evaluated by a fitness function, which is important to the GA (de Weck and Wilcox 2010) as it evaluates the quality of a gene for a certain aim[28].

[25] one example for this is described by Ashlock et al. (2011)
[26] Pech et al. (2015) created the algorithm for maze generation - yet visually the generated mazes equal dungeons and the authors themselves mention dungeon environments in their introduction
[27] as a complement to chromosomes so called phenotypes exist, which are what the chromosome represents - so as a rough example a 2D grid can be the chromosome of a dungeon
[28] in a dungeon could be number of rooms, percentage of accessible area, ...

The resulting numeric value can then be used to select a number of most fit genes/individuals to be reused/move on to a new generation (de Weck and Wilcox 2010). Furthermore the selected or additionally selected candidates[29] can be used to replace less fit individuals in two steps:

- *crossover*: two selected genes are split and exchanged to form two new genes (Fig. 9a)
- *mutation*: a certain number of bits/elements in a gene are randomly changed (Fig. 9b)

The above mentioned steps are repeated until the number of selected and/or the newly generated individuals is sufficient to replace the prev. population (de Weck and Wilcox 2010; Pech et al. 2015). Then again, the new population will be evaluated and it will be checked if the resulting Fitness values are sufficient to terminate the algorithm (or if other criteria like a certain number of iterations are met) (Pech et al. 2015). Otherwise another iteration will be carried out.



(a) Crossover **(b)** Mutation

Figure 9: GA Offspring Creation
Source:(Weise 2009)

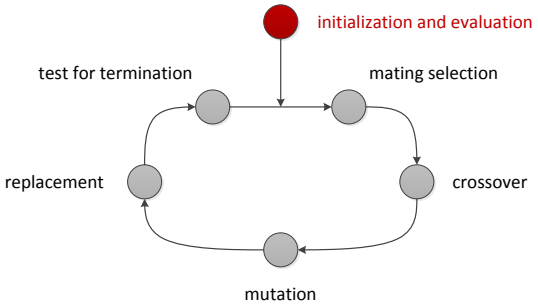


Figure 10: GA Algorithm Schema
Source: (de Weck and Wilcox 2010; Preuß 2015)

3.3.3 Dungeon Creation Algorithm

While the regular CA typically starts from a 'blank page' with randomly distributed rock cells, the Evolving CA use pre-generated maps as an input (Pech et al. 2015). To capture the visual characteristics nine attributes (see Table 9) are used, also illustrated in Figure 11 to clarify some terms[30] (potentially some attributes would need to be changed to apply the method for dungeons).
Moreover the CA is steered slightly different for the ECA, as it does not use the four variables r, n, T, M. It instead uses the following variables:

Variable	Description
S	number of cell states
N	size of the neighbourhood used for the CA

Table 8: Attributes for the Cellular Automata of the ECA - Source: (Pech et al. 2015)

[29] e.g. Tournament selection, where two or more members of a population are randomly chosen, compared and only the stronger one will move on to the crossover/mutation stage (de Weck and Wilcox 2010; Miller and Goldberg 1995)
[30] here it should be noted, that *traversable areas* are not marked in the picture - yet one traversable area is displayed by all accessible tiles (another traversable area would look similar but would not be connected)

Number of traversable areas.	Size of traversable areas.
Avg. size of all traversable areas.	Number of passageways.
Avg. length of passageways.	Number of rooms.
Avg. size of rooms.	Number of cul-de-sacs.
Number of dead-ends.	

Table 9: Attributes for ECA
Source: (Pech et al. 2015)

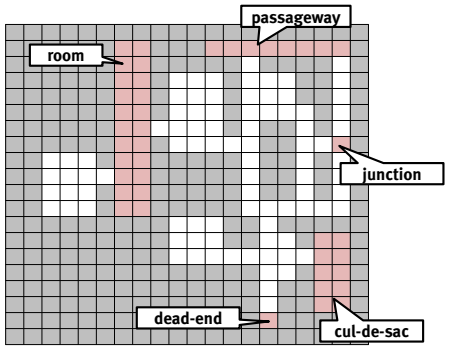


Figure 11: Illustration to clarify ECA Attributes
Source: (Pech et al. 2015)

As with the lack of the former threshold T the Cellular Automaton would lack a transformation rule, a new ruleset is introduced for the ECA. This ruleset does not have a fixed number like T to determine how a neighbourhood value is handled, but uses a rule table, that based on a given neighbourhood value is used to decide, how a cell should be transformed (Pech et al. 2015) (these rule tables also make up the genes or chromosomes that will be manipulated by the GA).
Pech et al. (2015) distinguish two types of rule tables or, as they call it - representations - differing in the following aspects (more explanations: Pech (2013) / representations: Ashlock et al. (2011)):

	Direct Representation	Indirect Representation
Application Case	simple Cellular Automata, max. two cell states	more complex CA
Output States	for each possible CA neighbourhood configuration	for every possible sum of neighbourhood values
Output State Representation	list of integers in lexicographic order	list of integers
# Neighbourhood Configurations	S^N[31]	$(S-1)\cdot N+1$

Table 10: Comparison of the different representation types for ECA - Source: (Pech et al. 2015)

How the cell transformation is handled can be best shown graphically in a simple 1D CA:

(a) Direct **(b)** Indirect

Figure 12: Representations/Rule Tables for the CA in ECA - Source: (Pech et al. 2015)

[31] neighbourhood size 1, two cell states: $N=3$ and $S^N=2^3=8$ (1D CA); $S^N=2^{(3\times3)}$ (2D CA) (Pech 2013)

Having discussed these basic elements of the ECA, the algorithm itself can now be discussed:

Codeline 1 in Listing 4

The whole procedure starts off with the initialization of the rule tables respecitively chromosomes, each cell being set to a random value in $[0, S-1]$ (for the generation of dungeons two states - path and rock - can already be enough) (Pech et al. 2015).

Codeline 2-5 in Listing 4

After the rule tables have been initialized, the evaluation starts by applying the associated CA to a collection (e.g. 100) of mazes/dungeons that have been generated before as a needed input for the CA[32] (Pech et al. 2015). In a next step Pech et al. (2015) use a series of image process techniques to obtain the nine Attributes for ECA without specifying the exact method[33].

Using the extracted attributes, for each generated layout an *attribute similarity measure* (ASM)[34] is calculated and finally for each individual/ruleset a fitness value FV is calculated (average of ASMs for each individual):

$$ASM = \sum_{i=1}^{9} \left(1.0 - \frac{|da_i - aa_i|}{ma_i}\right)^3 \times aw_i \quad \Big| \quad FV = \frac{1}{\#layouts} \sum_{j=1}^{\#layouts} ASM_j$$

Codelines 6-9 in Listing 4

In the next part of the ECA algorithm a new population has to be generated, where the overall procedure mostly follows the one described in the Overview over Genetic Algorithms.

As a first step, the five individuals with the highest FV are transferred to the next generation via elitist selection; the remaining 45 candidates for the new generation are found via tournament selection between five individuals and follow-up crossover and mutation (Pech et al. 2015). In difference to what is described for the general GA, crossover is only applied with a certain likelihood (e.g. 60%), which means that for every chromosome a random number generator draws a number in $[0, 1]$ and if it is smaller than the likelihood, crossover takes place (after an additional chromosome is added as two are needed for crossover) (Pech 2013; Pech et al. 2015).

The final step is the mutation of the chromosome (or after crossover: the two chromosomes), where each cell is changed with the probability of $\frac{1}{\text{chromosome length}}$ (using uniform mutation)[35] (Pech 2013).

Codelines 10-12 in Listing 4

Having created the new population, the algorithm must check, whether one of the following termination criteria is met or whether the CA evaluation and the population generation have to be repeated to further improve the solution (Pech et al. 2015):

- *Convergence*: last 100 consecutive runs did not increase FV by more than 0.0001
- *max. FV*: FV has reached its maximum of 1.0 and cannot be further improved
- *# Generations*: the other conditions are not met, but 5000 runs have been executed

[32] remember the standard CA that also needs a non-empty initial map-configuration, see section 3.2.2

[33] a rather precise overview over the techniques like erosion or region growing can be found in Pech (2013)

[34] da = desired attribute value // aa = attribute extracted value // ma = max. possible value // aw = attribute weighting factor → more information on each variable in Pech (2013)

[35] Pech (2013) and Pech et al. (2015) argue that they took most of the parameters for the GA from De Jong (1975) except the mutation parameter which they adapted to better fit the potentially varying chromosome lengths

```
initialize population // random value between [0,S-1]; S = #cell states
evaluate CA ruleset
  run CA with collection of perfect mazes/dungeons
  extract attributes from generated layouts using image process techniques
  evaluate extracted attributes based on set of goal attributes
repeat until new population is created
  select // elitist top 5 (only first step) + tournament selection
  crossover // single-point variant
  mutate // using uniform mutation
check if termination conditions are met
  yes - solution is found
  no - go to line 2 and continue search
```

Listing 4: Evolving CA Algorithm for Dungeon Generation - Source: (Pech et al. 2015)

3.4 Generative Grammars

While the previous approaches mostly focussed on generating dungeon maps with certain qualities like room count, or a natural look, the *Generative Grammar* has the intention to allow map-generation based on the gameplay respectively story (idea introduced by Dormans (2010) and taken up by van der Linden (2013)).

3.4.1 Areas of Application, Pros and Cons

In addition to the above mentioned general idea of Generative Grammars, this approach is also meant to improve the ease of use for designers (*controllability*, see Procedural Content Generation (for Games)) by allowing them to express the dungeon layout in a more high-level design-oriented way (Dormans 2010; van der Linden 2013), instead of more or less 'cryptic' variables as for Cellular Automata or Space Partitioning. Similar to what Pech et al. (2015) proposed for the CA, Dormans and Bakkes (2011) point out, that generative grammars can also be modified by evolutionary algorithms. Another PCG property that is satisfied by this approach, is *Speed*, as Dormans (2010) and van der Linden (2013) both characterize it as performant. Dormans and Bakkes (2011) even propose to use player modelling in combination with generative grammars to adjust the dungeon at play time (space, mission, difficulty, ...).
A last advantage, the syntactic correctness, is a side effect of using grammars and according to Dormans and Bakkes (2011) makes correctness tests and selection processes unnecessary.
One downside of using grammars is, that (at least at the moment)[36] grammars are still game-dependent, which means that two games require two different grammars (Dormans 2010). Dormans and Bakkes (2011) also restrict the idea that grammars make dungeon-generation easier for designers, as they figured out, that the knowledge of generative grammars is often not common among designers. This and the difficulties to foresee the final outcome (Dormans and Bakkes 2011) may lead to what Dormans (2010) calls maps having a '*random feel*' and '*lack[ing] overall structure*'.

Pro	Contra
map-structure and mission related	game-dependent
easier to use (high-level 'language')	designers lack knowledge
modifiable with evolutionary algorithms	difficult to estimate outcome
fast and adjustable to player	random/unstructured feel of maps
syntactical correctness	

Table 11: Advantages and Disadvantages of Generative Grammars
Source: (Dormans 2010; Dormans and Bakkes 2011; van der Linden 2013)

3.4.2 Overview over Grammar Types

Like for the previous algorithms, it makes sense to get an overview over the underlying ideas - in this case three different types of grammars, that in combination are used to create a dungeon map.

[36] van der Linden et al. (2013) have worked towards a more generic approach, where only the translator form grammar to real content is still game-dependent)

Generative Grammar (Fig. 13a)

This type can be seen as the 'basic' grammar, which is the basis for the other two types and is derived from linguistics, where among others Chomsky laid the foundation for generative grammars as constructs to produce all correct phrases of a language, based on an *alphabet* (symbols) and a *set of rules* (transformation of symbols to other symbols) (Dormans 2010; Hamp 2015; Pavle 2015). From there it was carried over to Computer Science as the basis for code parsers (Dormans 2010) and is formally defined as a 4-tuple $\langle V, \Sigma, S, P \rangle$ (also called Backus-Naur-Form[37]) (Adams 2002):

- V: is a finite alphabet, called *variables/nonterminal* symbols
- Σ: finite alphabet, called *terminal* symbols with $V \cap \Sigma = \emptyset$
- $S \in V$ as the *start symbol*
- P as *production rules* of ordered pairs $\langle \alpha, \beta \rangle$ with $\alpha, \beta \in (V \cup \Sigma)^*$ and α containing min. one symbol from V

To work with this, one starts to replace the start symbol S with one rule from the BNF, e.g. `S` $\rightarrow$ `e C G bm g` and than continues, till all non-terminal symbols V are replaced with terminal symbols Σ, e.g. `e t km km km km lm bl g`[38]. Combining the above mentioned ideas, it becomes clear that if words and rules are correctly given in some type of BNF, a computer cannot only analyse the language, but also use the given BNF to generate language, respectively missions/stories in case of dungeon generation (Dormans 2010).

Graph Grammars (Fig. 13b)

Graph Grammars build on the principles of Generative Grammars and thus are very similar to them, with the difference, that no strings are handled, but graphs with nodes and edges (Dormans 2010). Graph Grammars are used to build dungeons, as they provide more flexibility in rewriting things (see replacement for `G` in Fig. 13a and Fig. 13b) and as a result are considered to be more suitable to create desirable outcomes (Adams 2002).

Shape Grammars (Fig. 13c)

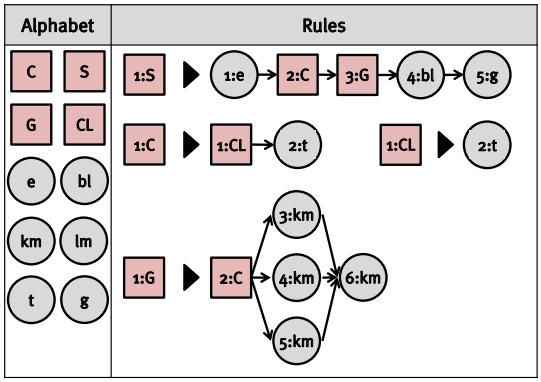
Shape Grammars, originating from work of Stiny and Gips (1972), build on the concepts of Generative and Graph Grammars, but instead of strings and nodes they use 2D shapes (Dormans 2010). The used shapes can represent any type of 2D layout element, like the walls and spaces in Fig. 13c or the test, key and lock rooms on page 6 of *Adventures in Level Design* by Dormans (2010). Like Graph and Generative Grammars, Shape Grammars work based on rewriting, so e.g. in Fig. 13c every connector could be replaced with one of the given rules to create a larger spatial structure.

Σ	*e* [entrance], *bl* [level-boss], *km* [multi-part Key], *lm* [lock for multi-part key], *t* [test], *g* [goal]	S	S [chain]
V	S [start], C [chain], G [gate], CL [chain linear]	P	$S ::= e\ C\ G\ bl\ g$ $C ::= CL\ t$ || $CL ::= t$ $G ::= km\ km\ km\ lm$

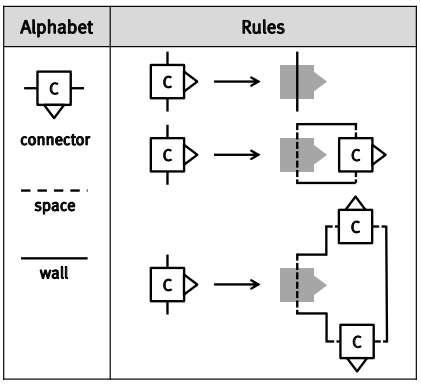
(a) Generative Grammar

[37] not called that way by Adams (2002), but the given notation resembles the BNF described e.g. in Vahrenhold (2013)

[38] intermediate steps: `e C G bl g` $\rightarrow$ `e CL t G bl g` $\rightarrow$ `e t t G bl g` $\rightarrow$ `e t t km km km lm bl g`



(b) Graph Grammar



(c) Shape Grammar

Figure 13: Different Grammar Types Overview - Source: (Dormans 2010)

3.4.3 Dungeon Creation Algorithm

The algorithm discussed in this subsection is primarily derived from Dormans (2010) and Dormans and Bakkes (2011), but also incorporates some elements of the approach of van der Linden (2013) and Adams (2002). Basis for this decision was the fact, that only Dormans (2010) and Dormans and Bakkes (2011) do not work towards any kind of implementation and thus focus on the description of the algorithm and necessary background information.

```
1  define symbols and vocabulary
2  define relationships and constraints
3  transform to graph grammar
4  define shape grammar
5    create min. one shape for each terminal graph node
6  build mission with graph grammar
7  build space/layout with shape grammar
8    for each mission element
9      find suitable shape element
10     place at random, suitable location
11     save reference to mission element
12 compute player model // optional
13 adapt mission/space/difficulty based on player model // optional
```

Listing 5: Generative Grammar Algorithm for Dungeon Generation
Source: (Dormans 2010; Dormans and Bakkes 2011; van der Linden 2013)

Codelines 1-2 in Listing 5

Right at the beginning, the dungeon designer must identify the basic elements of the dungeon story (and through this step also for the layout). This, in an easy case, comes down to set up a basic generative grammar as in Figure 13a, specifying the core elements, like in a dungeon case rooms, boss-enemies, keys etc. and on top of that basic relations, like a dungeon having rooms, rooms containing enemies and keys.

Codelines 3-5 in Listing 5

Based on the generated vocabulary and basic rules, a Graph Grammar is created as the basis for the story generation (Dormans 2010). Again, the reason basically is the greater flexibility compared to Generative Grammars, allowing non-linearity and more randomness (Adams 2002; Dormans 2010). As the Graph Grammar will only be the 'intermediate' step to generate the dungeon level, Dormans (2010) creates at least one shape for each terminal node in the Graph Grammar to enable the translation from mission to space. Multiple ones would also be possible, then one element would randomly be selected (Dormans 2010), creating greater diversity.

Codeline 6 in Listing 5

Before or also after the creation of the Shape Grammar, the specified Graph Grammar is used to generate the underlying story (Dormans 2010). This, as indicated in Overview over Grammar Types, works by replacing the start node (in Fig. 13b `1:S`) with what is specified in the ruleset. When all non-terminal nodes are replaced with terminal ones (so based on the example in Fig. 13b only grey circles would remain) a mission is created (Dormans 2010). Here it has to be noted that Fig. 13b only represents a very limited example, as typically multiple replacement rules for a non-terminal symbol will exist, to ensure diversity.

Codelines 7-11 in Listing 5

Given the mission in Graph Grammar, the dungeon structure will be created by iterating through the (terminal) nodes of the graph, placing a suitable shape into the map for each node (Dormans 2010). Diversity is ensured by randomly selecting the shape from multiple fitting ones and can be increased by using dynamic parameters to influence choice, e.g. to select more complex/difficult shapes in the final parts of the dungeon (Dormans 2010). Keeping references to the mission graph is a guarantee that e.g. a key containing shape will be placed before a gate shape (Dormans 2010).

Codelines 12-13 in Listing 5

Dormans and Bakkes (2011) propose not to stop the algorithm/generation process once a dungeon is generated, but to make use of the speed of the method to continuously modify the map. Based on an analysis of the actions and preferences of players, they propose to alter shape grammars or the mission graph dynamically, or to use terminal graph nodes representing different difficulty levels. To bring some of those elements into a given dungeon, Dormans and Bakkes (2011) introduce special non-terminal mission nodes (e.g. `?`) that are not replaced in the initial map generation, but can be filled up during a game in the dungeon.

Differences in the van der Linden (2013) approach to the one of Dormans (2010)

van der Linden (2013) takes a slightly different approach by using the software *Entika* to define objects and their relations already including parameters and semantics[39]. Instead of the general Generative Grammar he uses a so called *Gameplay Grammar*, defining action and subactions (e.g. `Acquire key ::= Kill Enemy → Loot key`). This is later translated to an initial graph with all top-level actions, which are than iteratively replaced with subactions. Based spatial proximity they are grouped together, before applying several optimization steps to the resulting graph to get a representation that an exisiting map generator for the target game *Dwarf's Quest* can work with.

[39] e.g. a player could have a certain level - based on that finding a key could either include fighting monsters or just searching different treasure chests (van der Linden 2013); more about semantics and Entika in (Kessing et al. 2012)

4 Limitations and Conclusion

Any reader who made it through the previous sections should now have a good overview over a quite diverse set of dungeon creation algorithms. At the same time, he/she most likely will have noticed the often very brief and abstract style in which the algorithms are presented. While this is inevitable for a seminar thesis due to length restrictions, it still represents a first limitation, as a more complete understanding of each of these algorithms will require further reading. The given references constitute a good starting point to gain deeper insights wherever required or desired.
Moreover not only the description of individual algorithms is limited - the same holds true for the selection of algorithms presented in this thesis. Only three categories of dungeon creation algorithms made it into this thesis (plus one variation of a category), while a multitude of other approaches is not discussed. Examples include:

- Agent-based dungeon growing (Shaker et al. 2015)
- Relative Placement (Valtchanov and Brown 2012)
- Genetic Algorithms (e.g. Hartsook et al. (2011))
- Constraint-Based (Roden and Parberry 2004)

And this again limits the overall view on dungeon generation, as it up to this part only considers the scientific point of view. Considering that PCG research strives for practical applicability, existing practical work can also be a valuable source for information, especially for anyone aiming at implementing a PCG dungeon game himself. Some examples cited in this thesis would include Hely (2013) with a tutorial for BSP trees, Simon (2009) with his 7 Year Roguelike project or Pedersen (2014b) with his tutorial on CA.

This thesis has three major contributions: The first one is supposed to be an easy introduction into the concept of PCG and existing constructive generation methods for dungeons. This includes a clarification of the basics of PCG, content, games and dungeons as well as simple descriptions for four algorithms, supported by pseudo-code snippets and illustrating graphics. The explanation of used techniques, as e.g. BSP trees for space partitioning, before explaining their usage in the creation algorithm, shall provide people with no background in Computer Sciene or related faculties with the necessary toolbox to understand the more specific dungeon creation algorithms.
A second contribution is the provision of information on algorithm application cases, advantages and disadvantages, allowing the reader to quickly compare the explained algorithms in order to find the right one for a given scenario.
The provision of a vast set of references and additional literature is the last contribution of this thesis, enabling the reader to continue learning about algorithmic dungeon creation approaches. Here the '*PCG Book*' by Togelius et al. (2015b) would be suitable for newcomers to the PCG domain, whereas the cited conference proceedings and papers are rather recommended for more experienced readers.

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