A caching approach to real-time procedural generation of cities from GIS data

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ABSTRACT

This paper presents a method for real-time generation of detailed procedural cities. Buildings are generated as needed from real GIS data, using modern techniques that can generate realistic content and without having a huge impact on the rendering system. The system uses a client-server approach allowing multiple clients to generate any part of the city the user wishes without requiring the full data-set, or any pre-generated models. The paper introduces the use of object oriented shape grammars to reduce redundant code and presents a parallel cache to allow real-time generation of detailed cities.

Keywords: Procedural Modelling, GIS Data, Buildings, Cities, Real-Time Rendering.

1 INTRODUCTION

Procedural modelling of urban environments has become an important topic in computer graphics. With the ever increasing demand for larger and more realistic content in games and movies, the time and cost to model urban content by hand is becoming unfeasible. Apart from the entertainment industry, large urban models are also desired for urban planning applications and emergency response training.

We present a client-server system capable of generating huge cities of any size without requiring the client to download large 3d geometrical data sets. Our main contributions are as follows:

1. We propose the use of object oriented shape grammars to combat redundancies when creating buildings with multiple different styles.
2. We introduce a multi-state parallel cache that procedurally generates the city's geometry before it becomes visible. We will demonstrate frame-rate improvements over a system that simply generates buildings as they are needed.

While many cache based approaches have been proposed for rendering large terrains, the use of such techniques has not been explored for procedural generation of urban models. Numerous problems occur as rendering the buildings takes much less time than generating them. We aim to tackle this problem with a simple solution that can be used with existing techniques for terrain paging.

After an overview of our system and how we can utilise GIS data to model real cities (Section 3), we then introduce the idea of object oriented shape grammars (Section 4) demonstrating how they can be used to make simple changes to a building without creating redundant code. In Sections 5 and 6 we present our cache based system that can generate huge cities in real-time with interactive frame-rates and evaluate it. Example code of object oriented shape grammars is listed in the Appendix for the interested reader.

2 RELATED WORK

This section will review current techniques for the procedural generation of 3d building models. We will mainly review systems that employ production systems as they have been the most successful at generating realistic content. Other approaches based on stochastic texture synthesis ideas are touched upon briefly.

Detailed architectural models can be created using production systems (a set of symbols that are iteratively replaced according to a well defined grammar) but require a modeller to manually write rules. Their strength lies in the ability to provide detailed descriptions and yet randomness in a structured way.

Parish et al. [24] introduced the idea of using L-Systems [26] to model architectural content. L-Systems are production systems that use the parallel replacement of symbols in a string to simulate a growth process. L-Systems have previously achieved a lot of success in modelling trees and plants [27, 23], but have limitations in modelling buildings (since a building structure is more spatially constrained and does not reflect a growth process).

Stiny pioneered the idea of shape grammars [33, 31, 32] which can be used for generating complex shapes within a given spatial area. Shape grammars have been used for the construction and analysis of architectural designs [5, 8, 34, 12]. However, Stiny's original shape grammar operates on sets of labelled points and lines and is difficult to implement on a machine because of the number of transformations that must be searched before a rule can be selected and applied.

Wonka et al. [37] modify the idea of shape grammars to better represent building facades. They use a split grammar in which building facade is derived using a sequence of split and repeat commands to subdivide a planar shape.

Müller et al. [21] expand on this idea by developing the CGA shape grammar. This grammar includes environmental parameters that allow a shape (a part of a derived facade) to query if it is occluded by something else in the city, thereby aiding the placement of windows and doors. CGA shape is continually being improved and has even been used to reconstruct archeological sites [22] and is used in commercial products like CityEngine [1].

Recently Kracklau et al. [13] presented a new generalised language based on Python. They can create powerful descriptions by passing non-terminals as parameters, thus enabling abstract templates to be defined.

Shape grammars alone are not sufficient to generate realistic roofs on buildings. Laycock et al. [14] demonstrate a technique to generate roof models in different styles from a building footprint. They modify the straight skeleton algorithm proposed in [7] to generate different roof types. Soon [30] describes an algorithm capable of modelling roofs common to east Asian buildings, like temples and pagodas.

A completely different approach to production grammars takes concepts from texture synthesis and applies them to 3D models. Texture synthesis traditionally extrapolates image data by incrementally adding bits of the image that best match a small neighbourhood. This can produce very convincing results [35, 6, 15].

Merrell and Manoch [18, 19, 20] present a method that takes an example model as input and can produce larger models that resemble it. Output models are still very random and lack the fine control that production systems provide. Synthesis based approaches to generating new models are still very slow and are thus not applicable for interactive applications.

Layout generation concerns the automatic layout of roads and placement of urban content that is crucial for generating an entire city. Urban planning applications require the possibility to view changes to city layouts and to see the effect a proposed road network would have on traffic congestion. Using procedural techniques, such changes can be made interactively which is a great improvement over manual systems.

Parish et al. [24] introduce the use of L-Systems to grow road networks in a similar way to branches on a tree. This was one of the corner-stone papers in the area of procedural cities. However, it is difficult to fine tune the results because the variables do not give enough control over the road layout.

Chen et al. [4] introduce the use of tensor fields to guide road network generation. The user edits the tensor fields using interactive techniques discussed in [38]. Users can then interactively edit individual roads in a quick and easy manner.

Aliaga et al. [3] take a different approach to reconfiguring road networks. Using vector data of roads they form a graph to represent road intersections and parcels of land. Then, using k-means clustering [17], user-deformed parcels are replaced with similar parcels from elsewhere in the city. In [2] they improve on this system to allow the synthesis of completely new areas of the city. Cities with different road structures can then be blended together.

Grueter et al. [9] use a lazy generation technique to construct a potentially infinitely large city. Buildings are constructed when they are visible in the view frustum. The system seeds a random number generator based on the building's coordinates, thereby allowing each building to maintain a persistent style. Whelan et al. [36] present a system that allows real-time interaction in modifying roads and tweaking parameters. The user provides a height map and lays the roads, after which the system automatically places buildings and other details. The buildings are simple extrusions with texture and bump maps. Recently Haegler et al. [10] presented a system capable of generating detailed cities in real-time by carrying out procedural generation on the GPU.

Cache based techniques have been used extensively in real-time rendering. Paging is a popular technique for rendering large terrains [28, 16, 39]. Slater et al. [29] present a caching system that exploits temporal coherency to accelerate view culling. Akenine-Möller et al. [11] discuss many modern real-time rendering techniques including level of detail, batch processing and imposters.

3 SYSTEM OVERVIEW

In this section we present a system that can produce large detailed virtual cities in real-time using GIS data. Previous approaches discussed in Section 2 focus on either pre-generating large cities or are limited to simple grid layouts and building geometry with random styles. The system presented continuously updates the city by streaming GIS data from a server along with style descriptions for every building, without interrupting the rendering system.

Urban GIS is preprocessed and stored in a database along with style descriptions for every building for quick referencing. This preprocessing step is explained in section 3.1. Style sheets that control the facade generation are loaded at run-time and are stored in a hashtable on the client's system. The geometry cache updates itself based on the camera's position in the environment, downloading the surrounding environment data from the GIS database. This includes the position and shape of building footprints and style parameters (such as texture id, height and style id) used for generating the buildings. This allows persistent generation of the city. The cache controls what geometry is procedurally generated based on its distance from the camera. Meshes for the roads and buildings are then batched together for efficient rendering and sent to the render system. This process is described in detail in Section 5.

3.1 Data Extraction from GIS

The GIS data recorded contains detailed urban planning information, which is stored in different semantic layers that make it easy to access the building layouts. However, since the data is simply represented by a set of poly-lines, it is necessary to determine which lines belong to the same buildings. Figure 1 illustrates this process. The following algorithm describes how to extract the building layouts:

1. Create a graph representing all the vertices and edges.
2. Start at the bottom left node which contains two or more edges.
3. Follow the least interior angle edges until the starting node is reached again, thus creating a cycle.
4. Decrement the degree of every node along the cycle.
5. Repeat from Step 2 until no nodes with a degree greater than one remain.

A similar approach was taken by Pina et al. [25], however, individual buildings are extracted as opposed to urban blocks. The extracted building footprints are then loaded into a database for quick referencing by the system. A similar technique is used to extract the roads and insert the road network graph into a database.

4 BUILDING GENERATION

Buildings are procedurally generated using split grammar rules based on [21]. The rules compose of *subdiv*, *repeat*, *insert*, *extrude*, *detrude* and *comp* commands, which can subdivide and decompose shapes into new ones.

Comp
Breaks a shape down into the lower dimensional shapes it is composed of. For example, a building is broken down into its composing facades;

Subdiv
Subdivides a shape along a given axis;

Repeat
Subdivides a planar shape several times to fit many new shapes of a given width;

Insert
Replaces a planar shape with an external model;

Extrude
Extrudes a planar shape, thereby creating a new volumetric shape;

Detrude
Detrudes a planar shape, thereby creating a new volumetric shape.

Combinations of these simple commands can produce complex architectural geometry, while building roofs are generated using the approach described in [14]. The rules are specified using a script with a parameterised L-System style syntax:

$$Pred: Exp \rightsquigarrow Command(params)\{Successor\}: Prob$$

If the Boolean *Exp*ression evaluates to $true$ then *Command* is carried out on the shape with ID *Pred*ecessor and the resulting output shapes are given the ID *Successor*. Multiple rules can be specified for the same *Pred*ecessor and one is chosen at random based on its *Prob*ability value. This allows some variability among generated shapes.

A simple compiler was built to parse the scripts at runtime and generate a hash table of C++ function objects. This allows the script to be applied extremely quickly to new buildings but also allows parameters to be changed at runtime.

4.1 Object Oriented Buildings

The production system presented in [21] contains a lot of redundant code between different building scripts. It is very cumbersome to rewrite entire building specifications just to make a specific change.

We propose the use of object oriented buildings as a solution to this problem. Figure 2 illustrates this idea. Buildings inherit everything from more abstract styles and only respecify certain aspects of the style. This is achieved by encapsulating semantically relevant production rules in labelled blocks. Each block is given a list of variables that can be changed at runtime or respecified by a child style. Code listings to generate the buildings in Figure 2 can be found in the Appendix. Buildings also inherit their parents' elements (i.e., 3D models that are imported and used to replace certain terminal symbols) and can add or remove from their parents' element set. We allow multiple meshes to be specified, corresponding to different levels of detail for the rendering system. Meshes are swapped with different level of detail meshes depending on their distance to the camera. In this implementation of the system the Ogre rendering engine was utilised to manage level of detail swapping and rendering of the scene. The use of object oriented building styles can simplify the writing of new styles and can link building styles together in a meaningful way.

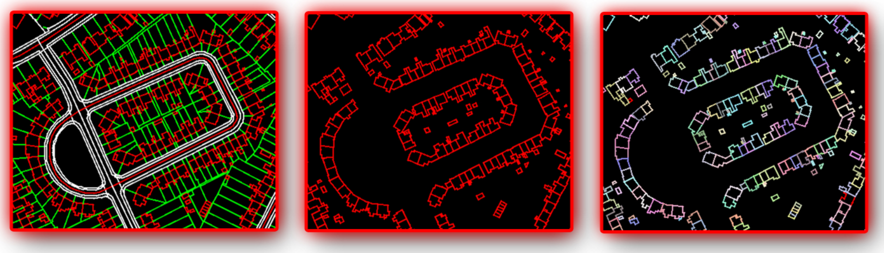


Figure 1: Extracting building footprints from GIS data (left). Layer containing buildings is first chosen by the user (middle), while buildings are then extracted by finding loops in the data (right).

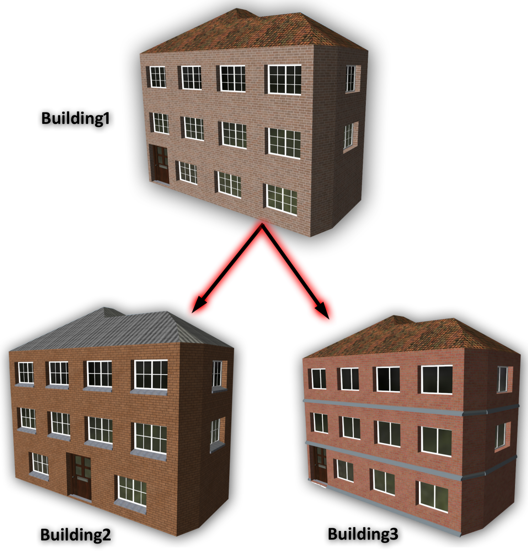


Figure 2: Building2 inherits from Building1, specifying how windowsills should be added. Building3 also inherits from Building1, adding a ledge to each floor. Code listings are provided in the Appendix.

5 REAL-TIME GENERATION

In this section we present our process for generating procedural cities in real-time.

5.1 Parallel Geometry Cache

In order to maintain a constant and high frame rate, building generation should not interrupt the rendering system. We achieve this by introducing a multi-state cache that stores geometry that is currently being generated. The system is based on the idea of paging geometry for rendering large terrains. The world is split into a regular grid as illustrated in Figure 4. The data in the cache has the following three states:

State 1 Geometry descriptions are downloaded from the database and the area is procedurally generated. (Outer white area in Figure 4).

State 2 Meshes are constructed and sent to the graphics card but are not yet rendered (Middle blue area in Figure 4).

State 3 Meshes currently being rendered (Inner green area in Figure 4).

Depending on the camera motion, grid squares that are likely to become visible in the near future are loaded. Geometry descriptions are downloaded from the GIS database, procedurally generated and inserted into the cache. This is done in a separate thread from the rendering system. Only squares that are close to the camera are rendered. If a square is not yet generated, the rendering thread will put it on the end of a queue and try to retrieve the next square.

5.2 Parallel Building Generation

With the trend in computing power drifting towards multi-processor architectures, it is desirable to take advantage of parallel computation. It is possible to procedurally generate multiple buildings at the same time by utilizing parallel processing techniques. Algorithm 3 presents a simple algorithm that can speed up building generation on multiprocessor systems.

```
while NewPage = getPageFromQueue()
  NumBldPerThd = NewPage.NumBlds/NumProc
  for x = 0 to numProccesors-1
     Thread[x] = ForkThread()
     Thread[x].MemoryPool = new MemoryPool
     Thread[x].BuildingList = distBuildings(NumBldPerThd)
     Thread[x].GenerateBuildings()
     NewPage.setBuildingMeshes(Thread[x])
  end for
   SynchroniseThreads()
end while
NewPage.BatchMeshes()
```

Algorithm 3: Algorithm for procedurally generating buildings in parallel.

Each thread maintains a memory pool that is reused for every building it generates, which reduces memory allocation bottlenecks. Threads must synchronise before writing to the cache so that buildings can be batched together for fast rendering.

6 RESULTS

To test the system, we conducted two separate benchmark, which were performed on a machine with the following specifications:

CPU	Intel(R) Core(TM)2 Duo CPU E8500 @ 3.16GHZ
RAM	4GB
GPU	NVIDIA GeForce 9800GT

First, a frame rate analysis of the system was taken while the camera was moved between two preset points,

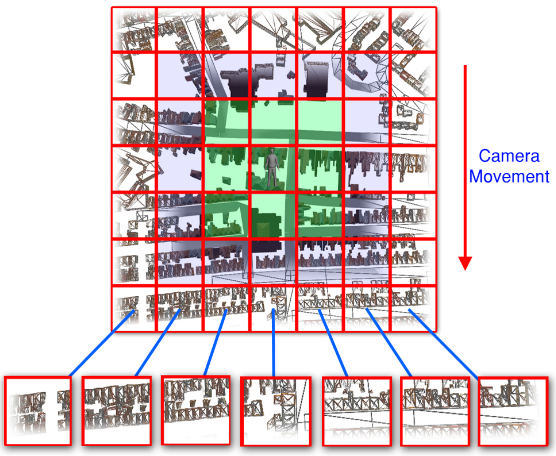


Figure 4: As the camera moves towards the geometry, new pages must be loaded. The pages are organised into a queue and processed in order of their distance to the camera. The buildings within each page should be shared among parallel executing threads.

both with and without the parallel geometry cache (Section 5.1). The results are given in Figure 5. While the camera travelled a distance of 800m in the scene, exactly 2,038 buildings were created. This had a significant effect on the frame rate of the system without a parallel cache. The sudden drops in frame rate correspond with new geometry pages being loaded and cause a jerk in the camera motion. In the system with the parallel cache there is much less jerking when pages are loaded and the overall frame rate stays within acceptable levels.

The second experiment performed was a multi-threaded processing benchmark. Four pages were generated consisting of 10, 100, 1000 and 10,000 buildings respectively. Processing time was logged for each of the pages with building generation distributed over different number of threads. The average results over ten repetitions are shown in Figure 6. A configuration with two threads running in parallel yielded the best performance on the dual core machine. Running the experiment with more threads than processors led to worse results because of the overhead of thread switching. However, this result suggests better performance could be achieved with a greater number of processing cores. Better results were obtained using larger page sizes with 10,000 buildings leading to a 27.48% increase in performance (We suspect that this is due the initial memory pool allocation assigned to each thread). Table 1 shows the number of buildings generated per second for the 10,000 building page test. Each building was set to be strictly the same shape, contained an average of 980 vertices and required 610 shape operations to generate.

Figure 7 demonstrates the type of architecture and scale of the city generated in the tests.

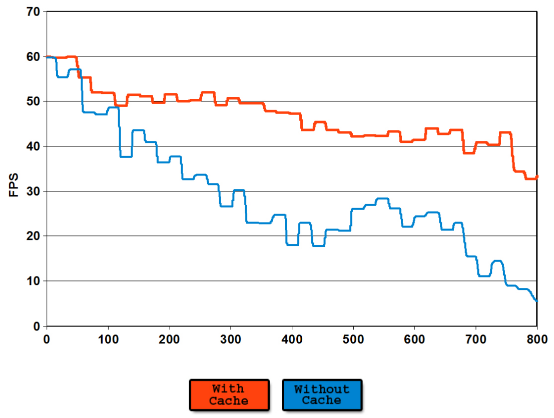
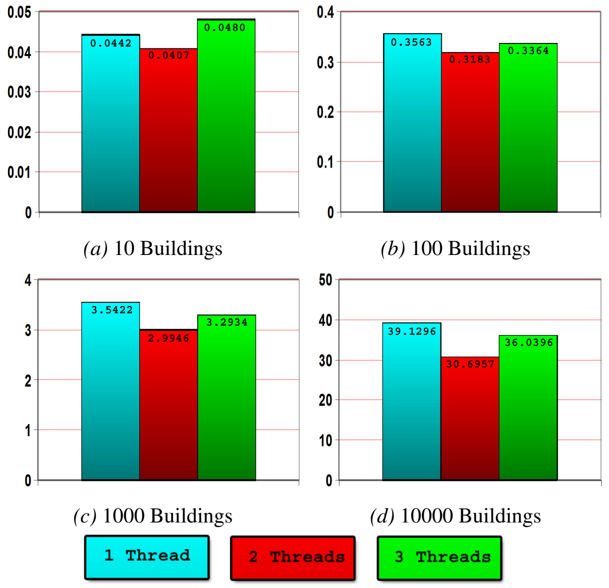


Figure 5: A comparison of results with and without the cache described in Section 5.1. The system with the cache has a much higher frame rate and less jerky movements of the camera. There was an average of 1,922 buildings in the scene at any time with 2,038 buildings created and destroyed over the distance.



(a) 10 Buildings

(b) 100 Buildings

(c) 1000 Buildings

(d) 10000 Buildings

Figure 6: Time in seconds to generate buildings with different levels of multithreading. On the dual core machine two threads yielded the best performance.

	Bld/Sec	Ops/Sec	Percent Increase
1 Thread	255.56	15,586.34	
2 Threads	325.78	19,868.86	27.48%
3 Threads	277.47	16,922.73	8.57%

Table 1: Benchmark of multi-threaded processing on the 10,000 building data set. Results are shown for the number of buildings generated per second, the number of shape operations (discussed in Section 4) performed per second and the percentage performance boost over a single threaded configuration.

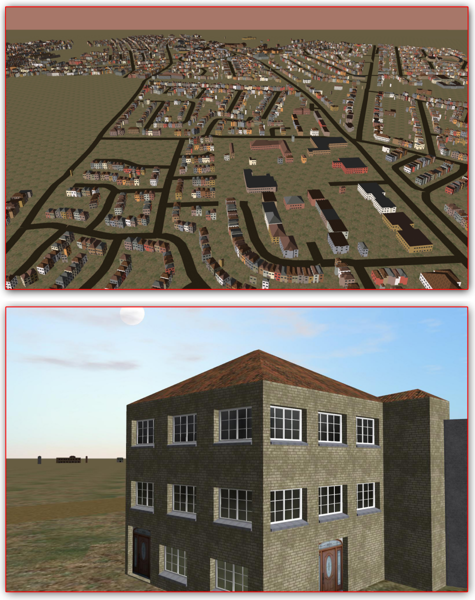


Figure 7: Output of the system

7 CONCLUSION

We have presented a system that can generate large virtual cities with detailed buildings in real-time. The system can be run over a network while allowing multiple clients with only one data set. We introduced the idea of object oriented building styles that can help reduce code redundancies and make it easier to specify multiple building styles. We also presented a set of benchmarking statistics calculated with different configurations of the system. The results showed that our parallel cache offers superior performance to that of a system that simply generates the buildings as they are needed. We also showed a performance benefit when utilising parallel generation on multi-core processors.

Regarding limitations, currently the system only generates buildings within a single page in parallel. The results from our experiment suggest that improved performance could be achieved by generating sets of pages in parallel, thus handling more buildings per thread and requiring less thread synchronisation. Rendering of the system could improved by implementing occlusion culling and better LOD techniques. In this implementation, different level of details are provided for a building's elements but not the shape of the building itself.

A SHAPE GRAMMAR SYNTAX

In this appendix we present the syntax of our object oriented shape grammar.

The listings correspond to the buildings shown in Figure 2. Semantically relevant production rules can be combined into meaningful blocks. Each block can have its own list of variables that may be changed at runtime. A child class inherits everything from its parents and may redefine a block of rules and its variables. In addition to defining a block of production rules, a class can also define a set of building elements (Listing 9). These elements correspond to terminal symbols in the production system, which should be replaced with external models. A series of meshes can be given to each element specifying a different level of detail. In our system, the distance at which to change a mesh is the same for each element and is specified by the cache system. As with the production rules, probabilities are given for the replacement of terminal symbols with 3D meshes.

```
class Building1 : ElementPack
{
  Footprint{
    FOOTPRINT ⇝
      extrude(BUILDING_HEIGHT){ BuildingVol } : 1
    BuildingVol ⇝
      comp ("facades"){ FACADE } : 1
  }

  Facade{
    var GroundFloorHeight 1

    FACADE : H > (GroundFloorHeight + 1) ⇝
      subdiv("Y",GroundFloorHeight,1r)
      { GROUND_FLOOR | UPPER_FLOORS } : 1
  }

  Ground_Floor{
    var EntranceWidth 0.75
    var DoorDepth 0.1

    GROUND_FLOOR: W > (EntranceWidth+1) ⇝
      subdiv("X",1r,EntranceWidth,0.1)
      { FLOOR | EntrancePanel |WALL } : 0.3
    GROUND_FLOOR: W > (EntranceWidth+1) ⇝
      subdiv("X",1r,EntranceWidth,1r)
      { FLOOR | EntrancePanel |FLOOR } : 0.44
    GROUND_FLOOR: W > (EntranceWidth+1) ⇝
      subdiv("X",0.1,EntranceWidth,1r)
      { WALL | EntrancePanel |FLOOR } : 0.3
    EntrancePanel ⇝ subdiv("Y",0.02,1r)
      { WALL | Entrance }
    Entrance ⇝ detrude(DoorDepth)
      { DOOR |WALL } : 1
  }

  Upper_Floors{
    var FloorHeight 1.0

    UPPER_FLOORS ⇝ repeat("Y",FloorHeight){FLOOR} : 1
  }

  Floor{
    var TileWidth 1.1

    FLOOR ⇝  repeat("X",TileWidth){TILE} : 1
  }

  Tile{
    var WindowDepth 0.1
    var WindowWidth 0.75
    var WindowHeight 0.5

    TILE ⇝ subdiv("X",1r,WindowWidth,1r)
      { WALL | Tile | WALL } : 1
    TileC ⇝ subdiv("Y",1r,WindowHeight,1r)
      { WALL |WindowPlane | WALL } : 1
    WindowPlane ⇝ detrude(WindowDepth)
      { WINDOW | WALL } : 1
  }
}
```

Listing 8: Listing for simple building

```
class ElementPack
{
  Elements{
    WINDOW:
      "window1LOD1.mesh" "window1LOD2.mesh" : 0.5
      "window2LOD1.mesh" "window2LOD2.mesh" : 0.5

    DOOR:
      "door1.mesh" : 0.2
      "door2LOD1.mesh" "door2LOD2.mesh" : 0.8

    LEDGE:
      "windowLedge1LOD1.mesh" "windowLedge1LOD2.mesh" : 1
  }
}
```

Listing 9: Listing for elements

```
class Building2 : Building1
{
  Tile{
    var LedgeHeight 0.075
    var WLedgeHeight (WindowHeight+LedgeHeight)

    TILE ⇝ subdiv("X",1r,WindowWidth,1r)
      { WALL | TileC | WALL }: 1
    TileC ⇝ subdiv("Y",1r,WLedgeHeight,1r)
      { WALL | WindowPlane | WALL }: 1
    WindowPlane ⇝ detrude(WindowDepth)
      { WindowPlaneInner | WALL }: 1
    WindowPlaneInner ⇝ subdiv("Y",LedgeHeight,1r)
      { LEDGE | WINDOW }: 1
  }
}
```

Listing 10: Building2 inherits everything from Building1 but specifies how windowsills should be added.

```
class Building3 : Building1
{
  floor{
    var TileWidth 1
    var LedgeHeight 0.075

    FLOOR ⇝ subdiv("Y",LedgeHeight,1r)
      {LEDGE | FloorU} : 1
    FloorU ⇝ repeat("X",TileWidth){TILE} : 1
  }
}
```

Listing 11: Building3 inherits everything from Building1 adding a ledge to each floor.

REFERENCES

[1] Procedural inc. - 3D modeling software for urban environments. http://www.procedural.com/.

[2] D. G. Aliaga, B. Beneš, C. A. Vanegas, and N. Andrysco. Interactive reconfiguration of urban layouts. *IEEE Comput. Graph. Appl.*, 28(3):38–47, 2008.

[3] D. G. Aliaga, C. A. Vanegas, and B. Beneš. Interactive example-based urban layout synthesis. *ACM Trans. Graph.*, 27(5):1–10, 2008.

[4] G. Chen, G. Esch, P. Wonka, P. Müller, and E. Zhang. Interactive procedural street modeling. *ACM Trans. Graph.*, 27(3):1–10, 2008.

[5] J. Duarte. *Malagueira Grammar - towards a tool for customizing Alvaro Siza's mass houses at Malagueira*. PhD thesis, MIT School of Architecture and Planning, 2002.

[6] C. Eisenacher, S. Lefebvre, and M. Stamminger. Texture synthesis from photographs. *CGF: Eurographics*, 27(2):419–428, 2008.

[7] P. Felkel and S. Obdrzálek. Straight skeleton implementation. In *SCCG: Spring Conference on Computer Graphics*, page 210–218, 1998.

[8] U. Flemming. More than the sum of parts: the grammar of queen anne houses. *Environment and Planning B: Planning and Design*, 14(3):323–350, 1987.

[9] S. Greuter, J. Parker, N. Stewart, and G. Leach. Real-time procedural generation of 'pseudo infinite' cities. In *GRAPHITE: Computer Graphics and Interactive Techniques*, page 87–ff, New York, NY, USA, 2003. ACM.

[10] S. Haegler, P. Wonka, S. M. Arisona, L. V. Gool, and P. Müller. Grammar-based encoding of facades. *CGF: Eurographics*, 29(4):1479–1487, 2010.

[11] J. Hasselgren and T. Akenine-Möller. PCU: the programmable culling unit. *ACM Trans. Graph.*, 26(3):92, 2007.

[12] H. Koning and J. Eizenberg. The language of the prairie: Frank lloyd wright's prairie houses. *Environment and Planning B: Planning and Design*, 8(3):295–323, 1981.

[13] L. Krecklau, D. Pavic, and L. Kobbelt. Generalized use of Non-Terminal symbols for procedural modeling. *CGF: Eurographics (to appear 2010)*, 2010.

[14] R. G. Laycock and A. M. Day. Automatically generating roof models from building footprints. In *Journal of WSCG*, 2003.

[15] S. Lefebvre and H. Hoppe. Appearance-space texture synthesis. In *ACM Trans. Graph.*, pages 541–548, Boston, Massachusetts, 2006. ACM.

[16] Y. Livny, Z. Kogan, and J. El-Sana. Seamless patches for GPU-based terrain rendering. *Vis. Comput.*, 25(3):197–208, 2009.

[17] J. B. MacQueen. Some methods for classification and analysis of multivariate observations. In *5th Berkeley Symposium on Mathematical Statistics and Probability*, pages 281–297, 1967.

[18] P. Merrell. Example-based model synthesis. In *I3D: Symposium on Interactive 3D Graphics and Games*, page 105–112, New York, NY, USA, 2007. ACM.

[19] P. Merrell and D. Manocha. Continuous model synthesis. *ACM Trans. Graph.*, 27(5):1–7, 2008.

[20] P. Merrell and D. Manocha. Constraint-based model synthesis. In *SPM '09: SIAM/ACM Joint Conference on Geometric and Physical Modeling*, page 101–111, New York, NY, USA, 2009. ACM.

[21] P. Müller, T. Vereenooghe, P. Wonka, I. Paap, and L. V. Gool. Procedural 3D reconstruction of puuc buildings in xkipché. In *VAST: Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*, page 139–146, 2006.

[22] P. Müller, P. Wonka, S. Haegler, A. Ulmer, and L. V. Gool. Procedural modeling of buildings. *ACM Trans. Graph.*, 25(3):614–623, 2006.

[23] R. Měch and P. Prusinkiewicz. Visual models of plants interacting with their environment. In *SIGGRAPH '96: Computer Graphics and interactive techniques*, page 397–410, New York, NY, USA, 1996. ACM.

[24] Y. I. H. Parish and P. Müller. Procedural modeling of cities. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 301–308. ACM, 2001.

[25] J. L. Pina, F. J. Serón, and E. Cerezo. Building and rendering 3d navigable digital cities. In *GI_forum*, pages 167–176, Salzburg, Austria, 2009.

[26] P. Prusinkiewicz and A. Lindenmayer. *The algorithmic beauty of plants*. Springer-Verlag New York, Inc., 1990.

[27] P. Prusinkiewicz, L. Mündermann, R. Karwowski, and B. Lane. The use of positional information in the modeling of plants. In *SIGGRAPH '01: Computer Graphics and Interactive Techniques*, pages 289–300. ACM, 2001.

[28] J. Schneider and R. Westermann. GPU-Friendly High-Quality terrain rendering. *Journal of WSCG*, 14(1-3):49–56, 2006.

[29] M. Slater and Y. Chrysanthou. View volume culling using a probabilistic caching scheme. In *Department of Computer Science, University College London*, pages 71–78. ACM Press, 1997.

[30] T. T. Soon. Generalized descriptions for the procedural modeling of ancient east asian buildings. In *Symposium on Computational Aesthetics in Graphics, Visualization, and Imaging(CAE'09)*, 2009.

[31] G. Stiny. Introduction to shape and shape grammars. *Environment and Planning B: Planning and Design*, 7(3):343 – 351, 1980.

[32] G. Stiny. Spatial relations and grammars. *Environment and Planning B*, 9(1):113–114, 1982.

[33] G. Stiny and J. Gips. Shape grammars and the generative specification of painting and sculpture. In C. V. Friedman, editor, *Information Processing '71*, page 1460–1465, Amsterdam, 1972.

[34] G. Stiny and W. J. Mitchell. The palladian grammar. *Environment and Planning B: Planning and Design*, 5(1):5 – 18, 1978.

[35] L. Wei, S. Lefebvre, V. Kwatra, and G. Turk. State of the art in example-based texture synthesis. In *Eurographics 2009, State of the Art Reports, EG-STAR*. Eurographics Association, 2009.

[36] G. Whelan, G. Kelly, and H. McCabe. Roll your own city. In *Digital Interactive Media in Entertainment and Arts*, pages 534–535, Athens, Greece, 2008. ACM.

[37] P. Wonka, M. Wimmer, F. Sillion, and W. Ribarsky. Instant architecture. *ACM Trans. Graph.*, 22(3):669–677, 2003.

[38] E. Zhang, J. Hays, and G. Turk. Interactive tensor field design and visualization on surfaces. *IEEE TVCG: Transactions on Visualization and Computer Graphics*, 13(1):94–107, 2007.

[39] Z. Zhou, B. Cai, D. Zhang, and X. Zhang. Paged cache based massive terrain dataset Real-Time rendering algorithm. In *ICIECS: Information Engineering and Computer Science*, pages 1–4, 2009.