AMUSE:
Acquiring and Modeling Urban Simulation Environments

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Motivation

- Visualization of large urban environments is a great challenge for computer graphics
  - An urban environment is a collection of buildings and roads spanning a large area of land and arranged into neighborhoods, blocks, and parcels

Motivation

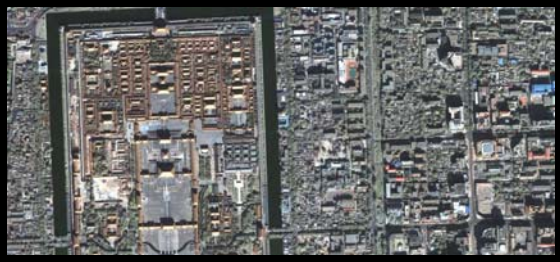
- Lafayette, Indiana

Motivation

- Indianapolis, Indiana

Motivation

- Beijing, China



Motivation

- Rome, Italy

Motivation

- Paris, France

Applications

- Urban Planning
  - What would a proposed neighborhood look like?
  - What would an area look like after population growth?
  - What would happen is we put a road here? (road planning)
  - Architectural designs wish to use common building blocks yet have unique and interesting spaces; can we extrapolate a city given a set of building blocks?

Applications

- Emergency Management
  - Can we create a model of a very large urban space to train emergency response personnel?
  - Can we plan evacuation routes and suggest emergency deployments?
  - Can we prioritize policing and resource deployment?
  - Given an urban model struck by a disaster/attack, we can deploy an emergency-relief communication network?
  - Can we deploy approximate structural information, via a PDA, to rescuers using both the urban model and the emergency-relief communication network?

Applications

- Reconnaissance and Rapid Prototyping
  - Can we rapidly build a prototype of an (enemy) location from aerial views?
  - Can we specify the most beneficial places from where to obtain ground views so as to build an urban model for soldier training and other simulations?
  - If an environment is changing, can we indicate from where we need the most updates?

Challenge

- Modeling large urban spaces typically requires significant manual effort, storage, and computation
- Dense urban areas are particularly difficult because they are both very complex and very widespread
  - Size of the environment makes obtaining detailed structural information prohibitive, leaving us with only sparse information

Observations

- Large urban environments exhibit significant repetition
  - Similar structures are repeated at the global level; however, they maintain individuality in local detail
- Widespread digital meta-data is available
  - High-resolution aerial views
    - e.g., 6 inch/pixel
  - City/county/parcel boundaries, road networks, basic building information
    - e.g., input to Google Maps

Approach

- Perform an inverse urban modeling task by inferring the 2D layout of an existing environment
  - Procedural methods have the advantage of exhibiting a high-degree of detail amplification, e.g. using a small number of parameters yields significant plausible details
- The resulting grammar allows us to
  - create modifications to the existing urban environments, in the style of the original
  - determine the most representative areas and layouts

Example: Changing Urban Spaces

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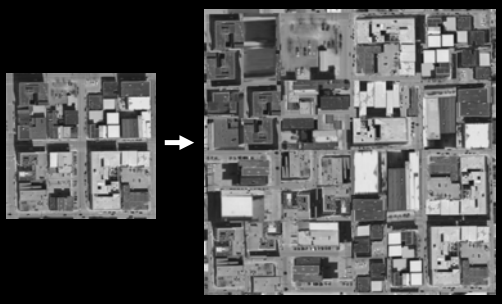
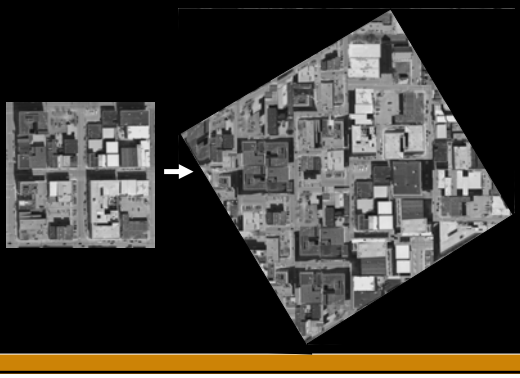
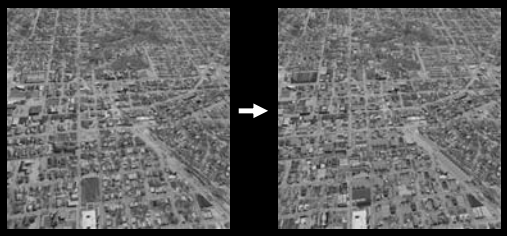


Example: Changing Urban Spaces



Example: Simplifying Urban Spaces



Thousands of parcels/buildings

Dozens of parcels/buildings

Related Work

- Forward-generating grammars (L-systems) for creating plants, cities, and buildings
  - Specify a grammar and few initial parameters, then "grow" the structure
  - × Not based on an actual real-word layout or city
- Photogrammetric Reconstruction and IBMR
  - Build a model from photographs (e.g., Façade, Lightfields, robot-based acquisition)
  - × Requires specialized acquisition systems and does not scale
- Inspiration
  - Epitomes and Vector Quantization
  - Build-by-Number
  - One paper: inferring plant L-system parameters from photographs

Terminology and Assumptions

- Parse
  - From aerial views and meta-data, create a set of production rules and a set of terminals
    - e.g., string to grammar
- Derive
  - Using the production rules, terminals, and a starting configuration, create an urban layout
    - e.g. grammar to string

Terminology and Assumptions

- Parcel
  - consists of a piece of bounded land; might contain building structures
- Block
  - Collection of adjacent parcels; interior boundaries are all imaginary; exterior boundary is a road; all parcels have access to road (egress rule)
- Neighborhood
  - Collection of blocks, separated by roads, and mostly of the same classification (e.g. “residential”, “commercial”, “industrial”, “downtown”, etc.)
- Region
  - Collection of neighborhoods, usually separated by major roads

Terminology and Assumptions

- Production
  - Given a region | neighborhood | block, partition by a road | boundary
    - Assumptions (for now): regions are convex polygons, partitions are polylines, production produces two children
- Terminal
  - Is a parcel
  - May or may not contain building contours

Methodology

- 1. Parsing
  - How to parse aerial views and their metadata
- 2. Terminal Simplification
  - Reducing the number of terminals
- 3. Production Simplification
  - Reducing the number of productions
- 4. Novel Derivations
  - Making new layouts

Methodology

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1. Parsing

- Parse aerial views in a top-down fashion to produce a set of production rules for creating the urban layout
- Existence Question
  - Does such a grammar exist?
- Answer:
  - Yes! It is exactly one production rule for each partition and exactly one terminal for each parcel
- *The interesting work is in simplifying and compacting the grammar so that it can be used in a flexible fashion*

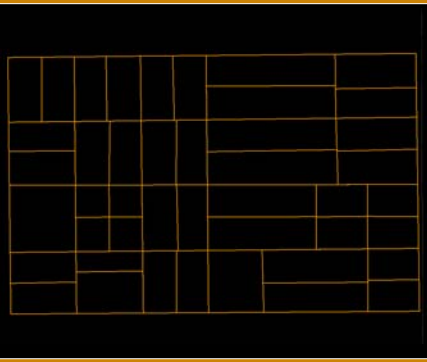
Example Aerial View I

Example Metadata I

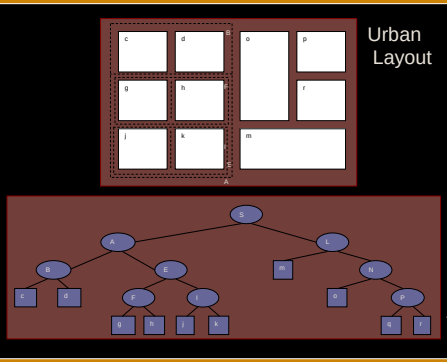
Example Aerial View II

Example Metadata II

Example Metadata II



Parse Tree



Production Rules

S → AL
A → BE
L → mN
B → cd
E → FI
F → gh
I → jk
N → oP
P → qr

~regions
~neighborhoods
~blocks

(lower case = terminals)
(upper case = region|neighborhood|block)

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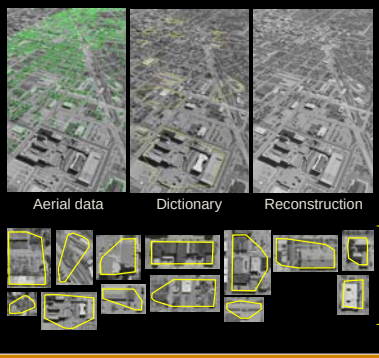
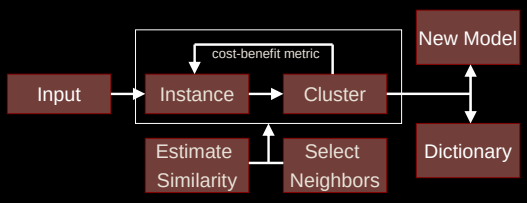
2. Terminal Simplification

- Reduce the number of terminals
  - Find a compact "dictionary" of urban structures
- Serves to
  - make grammar more compact
  - compress the data
    - e.g. image compression
  - prioritize the terminals
    - e.g. guides which parcels should be captured in more detail

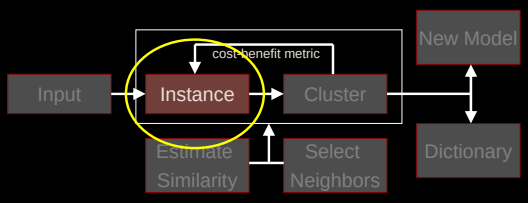
Urban Dictionaries



Simplification Pipeline



Simplification Pipeline



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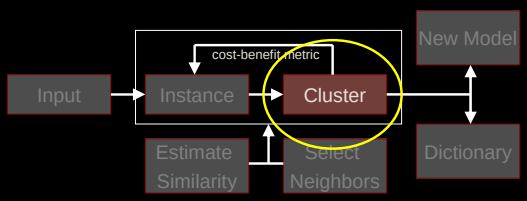
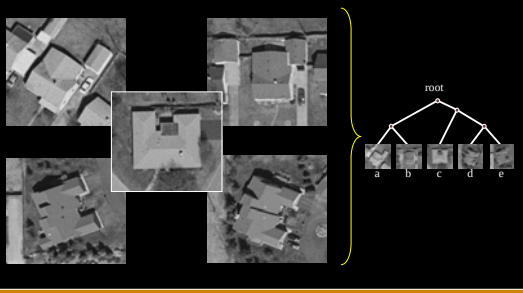
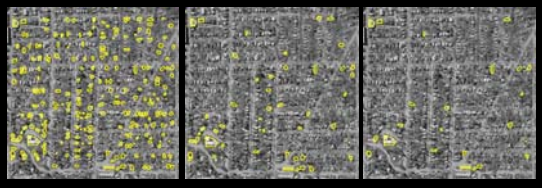


Instancing

- Global redundancy is exploited by growing a bottom-up hierarchy of equivalence classes



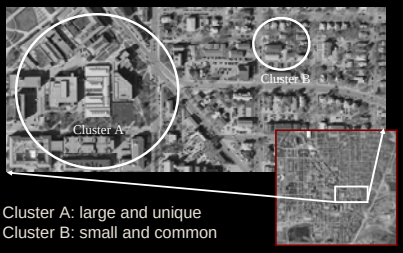
Instancing



Increasing error (and smaller number of equivalence classes)

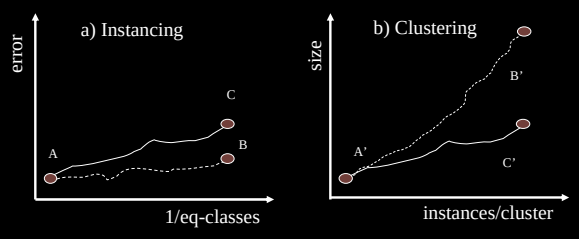
Clustering

- By combining instantiation with spatial clustering, we find spatially compact sets of representative urban areas

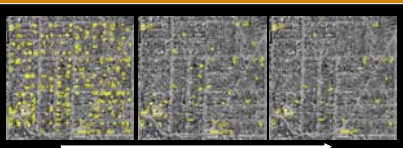


Cluster A: large and unique
Cluster B: small and common

Instancing vs. Clustering



Instancing vs. Instancing-and-Clustering



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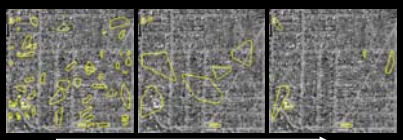
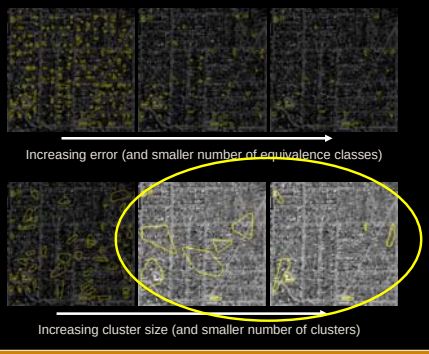


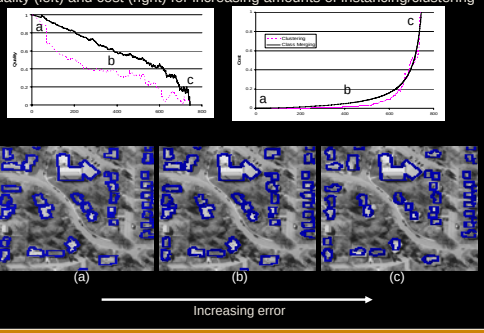
Increasing cluster size (and smaller number of clusters)

Instancing vs. Instancing-and-Clustering

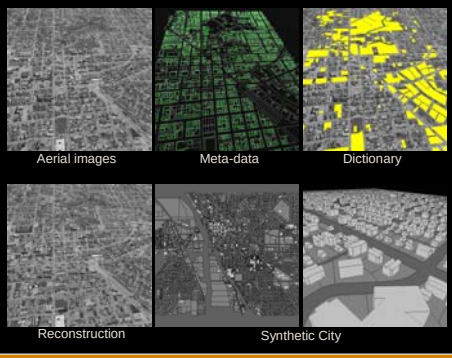


Instancing and Clustering

Quality (left) and cost (right) for increasing amounts of instancing/clustering



Example Terminal Simplifications



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3. Production Simplification

- Goal
  - Find a set of representative "rules" of the urban environment that can instantiate the same space, new spaces, and similar spaces
- Method
  - Find a dictionary of "rules" to build-up the urban space, for example:
    - Discover the rules by analyzing the layouts
    - Provide core rules that can represent all possible layouts

3. Production Simplification

- Rule Clustering
- Rule Canonization

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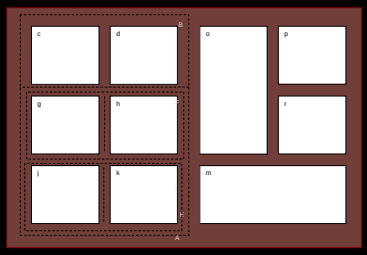
Recall the Original Production Rules…



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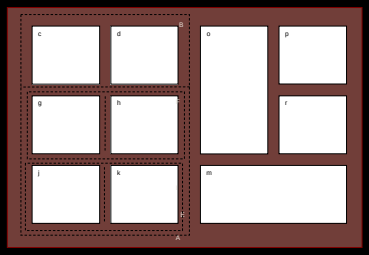
Full specification of the production rules

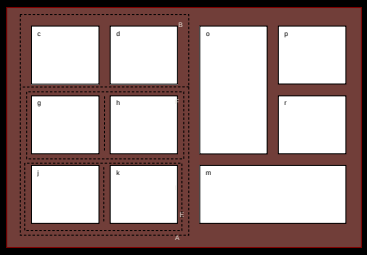
Alternate Rule Notation



$S \rightarrow A_0\ A_1^{180}$
$A_0 \rightarrow B_0E_0$
$B_0 \rightarrow cc$
$E_0 \rightarrow B_0B_0$
$A_1^{180} \rightarrow E_1m$
$E_1 \rightarrow mB_1^{90}$
$B_1^{90} \rightarrow cc$

Shape = letter; position = subscript; rotation = superscript

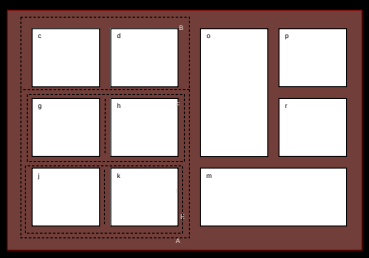
Rule Shape Similarity



S → AA
A → BE | mE
B → cc
E → BB | mB

Rules grouped based on similar shape but *ignoring* differences in location and rotation

Rule Shape Similarity



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= "Cluster by similar shape"

Rules grouped based on similar shape but *ignoring* differences in location and rotation

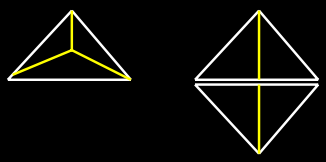
Rule Clustering

- Similarity(A,B) =
  - W_1ShapeSim(A,B) + W_2LocationSim(a,B) + W_3PositionSim(A,B) + W_4PartitionSim(A,B) + W_5TypeSim(A,B)
- Production rule clustering:
  - Define each rule by a n-dimensional vector
  - Perform k-means clustering to obtain k clusters of rules
  - Choose a representative rule from each cluster
- Effectively "infer" the most popular/representative production rule styles

Note: ???

Rule Canonization

- Reduce the full grammar to a more compact one using only a small number of flexible yet powerful canonical production rules
- Consider triangles:



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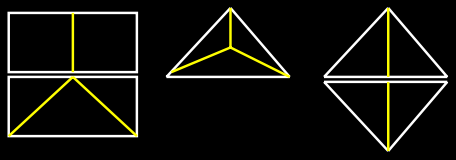
- Consider rectangles:



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Peel | Rectangular partition | Triangular partition | Create an Island | Etc…

Note: ???

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Novel Derivations

- Given production rules and an initial structure, derive an urban layout
- Examples:
  - Change original urban space
  - "Move a road" in the original urban space
  - Fill a new region with an urban space similar to the original
  - Grow an urban area

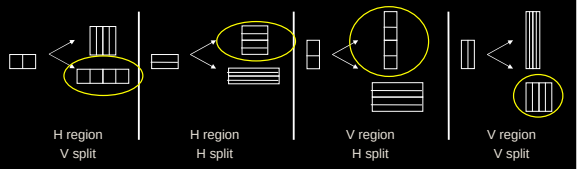
Novel Derivations

- Need to support subset of affine transformations:
  - Translation (e.g., "move a region")
  - Rotation (e.g., "re-orient a neighborhood")
  - Scale (e.g., "stretch/squish a block")

Transformations

- Translation
  - Easy to handle
- Rotation
  - Easy to handle
- Scale
  - ???

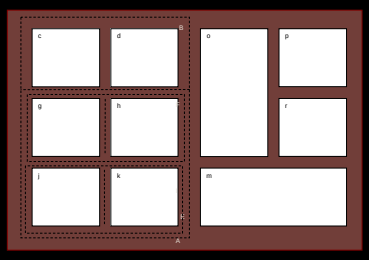
Observation: Scaling/Stretching



Conclusion:

- V stretches handled by H partition
- H stretches handled by V partition

Production Rules Revisited…



$S \rightarrow^{V} AA$
$A \rightarrow^{H} BE \mid mE$
$B \rightarrow^{V} cc$
$E \rightarrow^{H} BB$
$E \rightarrow^{V} mB$

Example Derivations

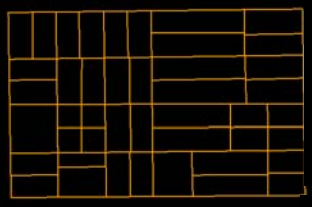
- Original urban space
  - $S \rightarrow AA$
  - $S \rightarrow BEmE$
  - $S \rightarrow ccBBmmB$
  - $S \rightarrow cccccmmcc$
- Stretched urban space
  - $S \rightarrow AA$
  - $S \rightarrow BEmE$
  - $S \rightarrow BEBEmEmE$
  - $S \rightarrow ccBBccBBmmBmmB$
  - $S \rightarrow ccccccccccmmccmmcc$

Note: for simplicity, these derivations are showing 1D strings – data is really 2D

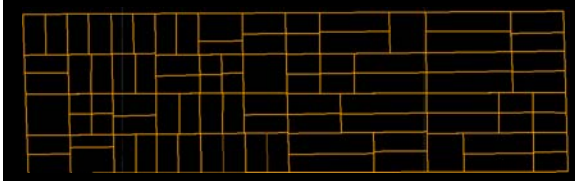
Original Urban Space I

Original Urban Space I

Original Urban Space I



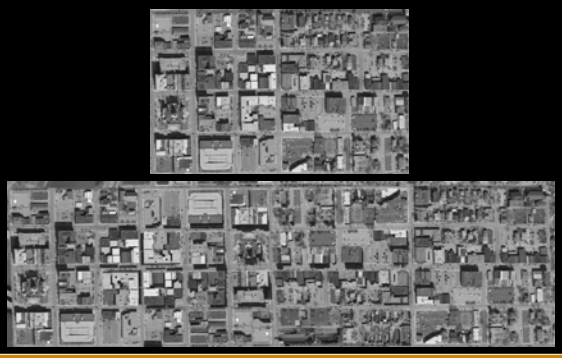
Stretched Urban Space I



Stretched Urban Space I

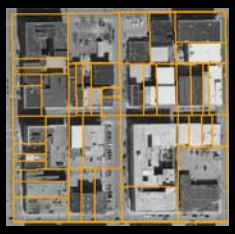
Stretched Urban Space I

Original vs. Stretched I

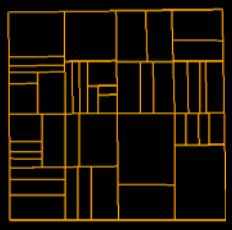


Original Urban Space II

Original Urban Space II



Original Urban Space II



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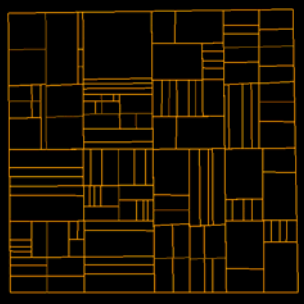

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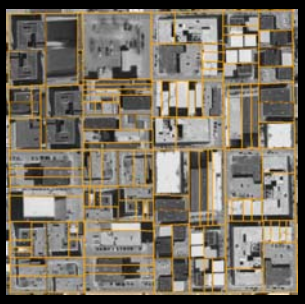

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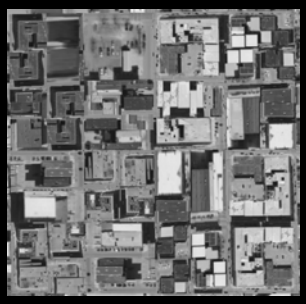
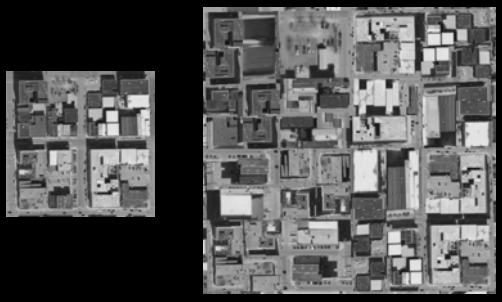
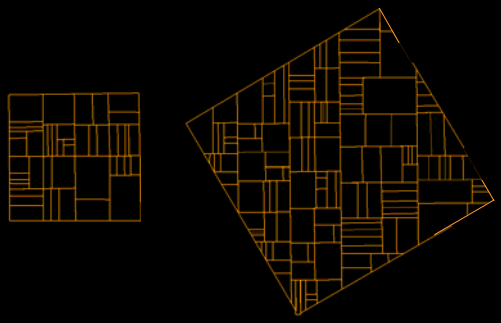


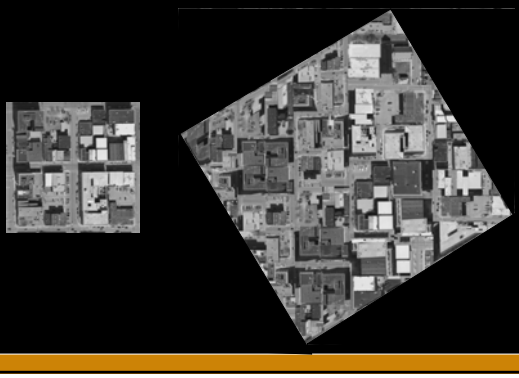
Original vs. Stretched II



Original vs. Stretched III



Original vs. Stretched III



Demo

Conclusions

- Urban Modeling is fun!
- Ability to be able to take views of an entire urban space and make an editable model out of it is very enticing
- Similar to fractal-based compression, the key is to find a good set of generators
  - Fortunately, urban environments offer significant amount of structure (and repetition) which we can exploit

Future Work

- Procedural Simplification
  - Specify canonical procedural rules?
  - Infer canonical procedural rules?
- Obtain data for a larger/more-interesting set of cities
  - Chicago, Rome, Paris, Cusco, etc.
- Full Inverse Modeling
  - Combine with Build-by-Numbers
- Applications
  - Road planning
  - Growth algorithms
  - Rapid prototyping

Thank you!