Procedural Content Generation

Lecture 1: Introduction
Autumn 2010
IT University of Copenhagen

Julian Togelius

What is PCG in games?

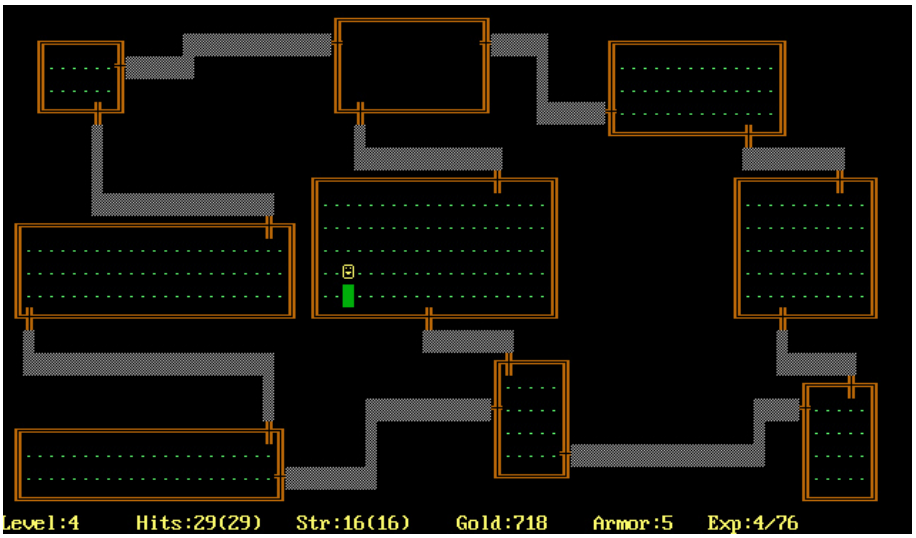
- Procedural Generation: with no or limited human intervention, algorithmically
- of Content: *not* NPC behaviour, *not* the game engine, things that affect gameplay
- in Games: computer games, board games... any kind of games

Game content, e.g.

- Levels, tracks, maps, terrains, dungeons, puzzles, buildings, trees, grass, fire, plots, descriptions, scenarios, dialogue, quests, characters, rules, boards, parameters, camera viewpoint, dynamics, weapons, clothing, vehicles, personalities...

History: Runtime random level generation

- Rogue-2D



1980

History: Runtime random level generation

- Dwarf Fortress-3D

2007

History: Runtime random level generation

- Tribal Trouble

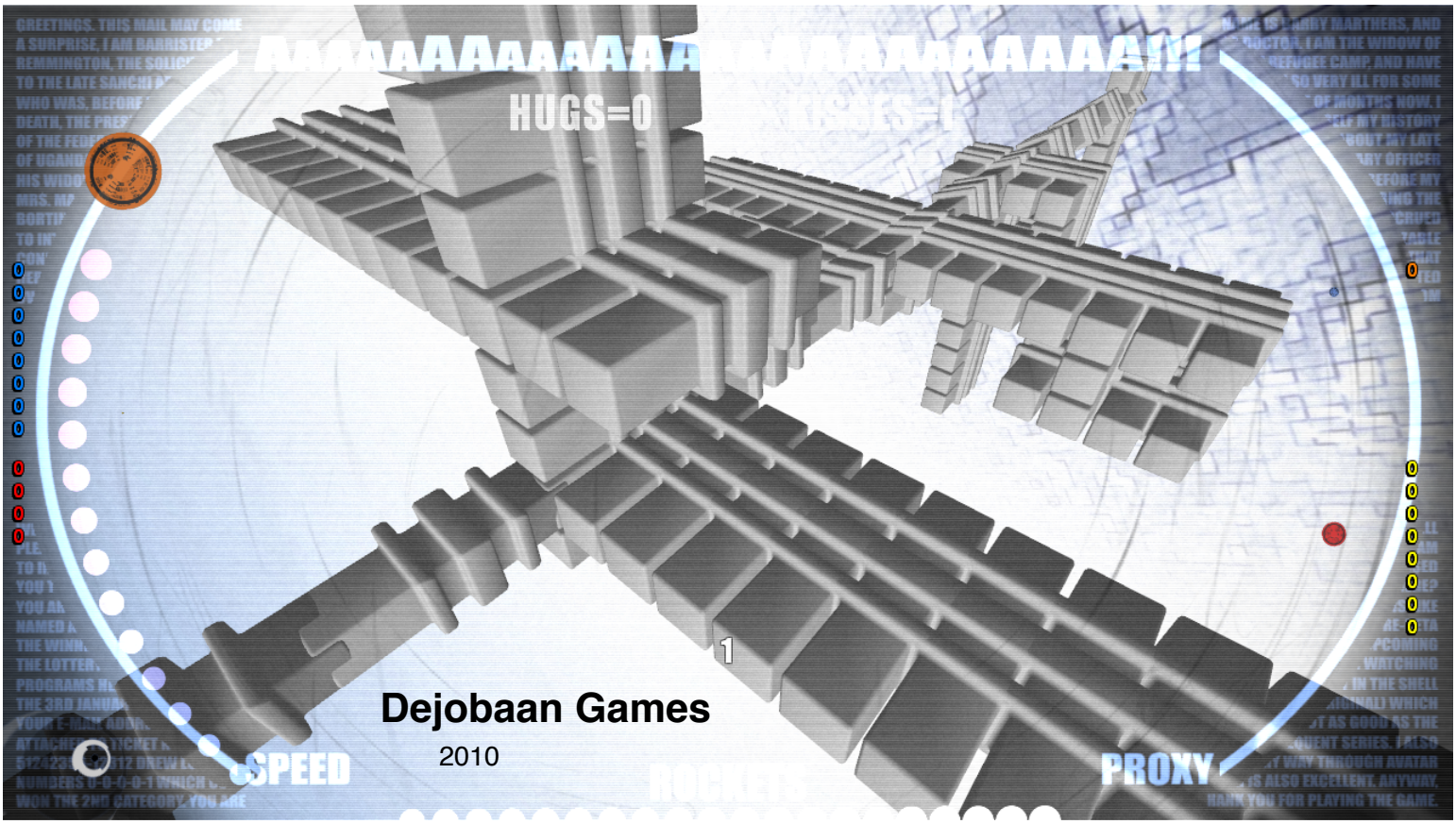
2005

Diablo

2008

Civilization IV

2005



SpeedTree

Sudoku

9			1					5
		5		9		2		1
8				4				
				8				
			7					
				2	6			9
2			3					6
			2			9		
		1	9		4	5	7	

The future...

- Can we drastically cut game development costs by creating content automatically from designers' intentions?
- Can we create games that adapt their game worlds to the preferences of the player?
- Can we create endless games?
- Can the computer circumvent or augment limited human creativity and create new types of games?

In general,

PCG > randomness

A taxonomy of PCG

- Online/Offline
- Necessary/Optional
- Random seeds/Parameter vectors
- Stochastic/Deterministic
- Constructive/Generate-and-test

Online/Offline

- Online: as the game is being played
- Offline: during development of the game

Necessary/Optional

- Necessary content: content the player needs to pass in order to progress
- Optional content: can be discarded, or bypassed, or exchanged for something else

Stochastic/ Deterministic

- Deterministic: given the same starting conditions, always creates the same content
- Stochastic: the above is not the case

Random seeds/ Parameter vectors

- a.k.a. dimensions of control
- Can we specify the shape of the content in some meaningful way?

Constructive/ Generate-and-test

- Constructive: generate the content once and be done with it
- Generate-and-test: generate, test for quality, and re-generate until the content is good enough

The Search-based Paradigm

- A special case of generate-and-test:
  - The test function returns a numeric fitness value (not just accept/reject)
  - The fitness value guides the generation of new candidate content items
- Usually implemented through evolutionary computation

Evolutionary computation?

- Keep a population of candidates
- Measure the fitness of each candidate
- Remove the worst candidates
- Replace with copies of the best (least bad) candidates
- Mutate/crossover the copies

Lecture 3: Plants and L-systems

Procedural Content Generation, Autumn 2010

Julian Togelius

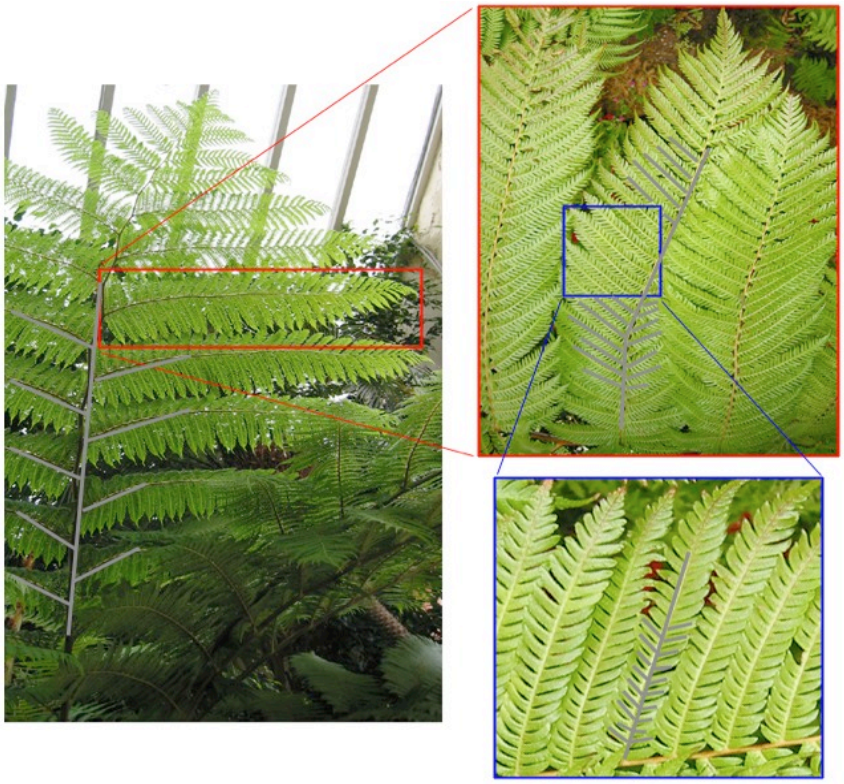
(some material borrowed from Gabriela Ochoa)

Plants?

- Core feature of the natural world... therefore of many games
- Need for believability
  - Infinitely detailed
  - Similar and recognizable, but not identical
- Need for compact representation
- Need for automatic large-scale generation

SpeedTree

Self-similarity



Self-similarity

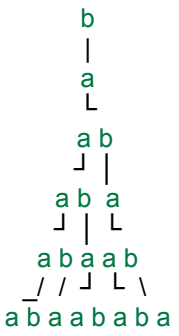
- Nature has obviously thought out some clever way of representing complex organisms using a compact description...
- ...permitting individual variation...
- ...why is this relevant for us?

L-systems

- Introduced by Aristid Lindenmeyer 1968, to model plant development
- Creates strings (text) from an *alphabet* based on a *grammar* and an *axiom*
- Closely related to Chomsky grammars (but productions carried out in parallel, not sequentially)

An example L-system

- Alphabet: {a, b}
- Production rules (grammar):
  a>ab
  b>a
- Axiom: b



Example of a derivation in a DOL-System

Types of L-systems

- Context-free: production rules refer only to an individual symbol
- Context-sensitive: productions can depend on the symbol's neighbours
- Deterministic: there is exactly one production for each symbol
- Stochastic: several productions for a symbol

A graphical interpretation of L-systems

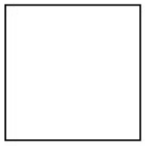
- Invented/popularized by Prusinkiewicz 1986
- Core idea: interpret generated strings as instructions for a turtle in turtle graphics
- Read the string from left to right, changing the state of the turtle (x, y, heading)

Example graphical L-system

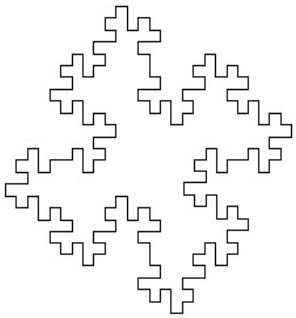
- Alphabet: {F, f, +, -}
- F: move the turtle forward (drawing a line)
- f: move the turtle forward (don't draw)
- +/-: turn right/left (by some angle)

Graphical L-system

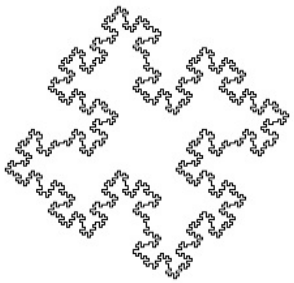
- axiom: F+F+F+F
- grammar:
  F>F+F-F-FF+F+F-F
- Turning angle: 90°



n=0



n=1



n=2

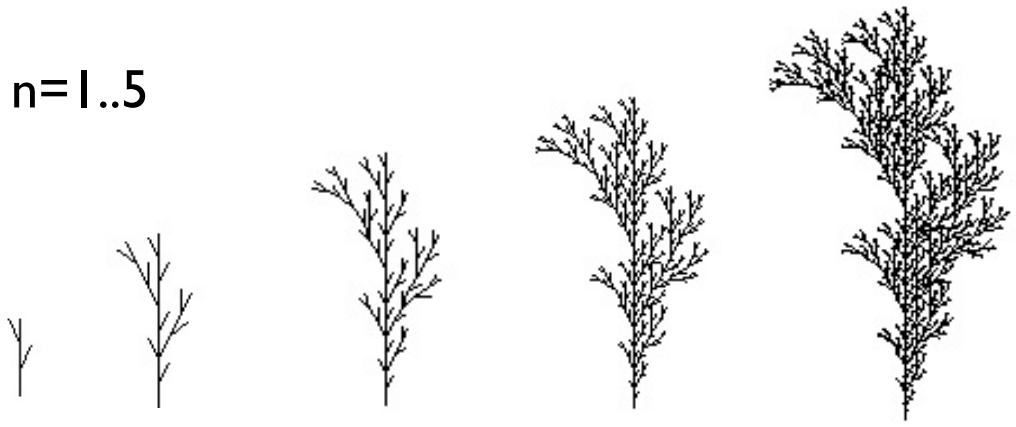
Bracketed L-systems

- Alphabet: {F, f, +, -, [,]}
- [: push the current state (x, y, heading of the turtle) onto a pushdown stack
-]: pop the current state of the turtle and *move* the turtle there *without drawing*
- Enables branching structures!

Bracketed L-systems

- Axiom: F
- Grammar: F>F[-F]F[+F][F]
- Turning angle: 30°

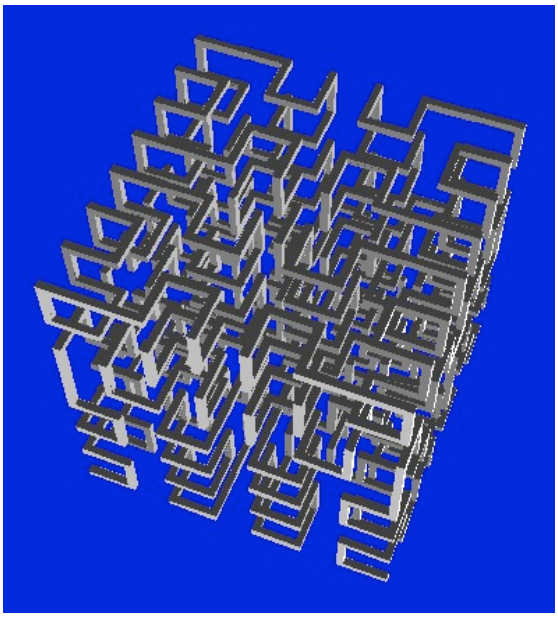
n=1..5

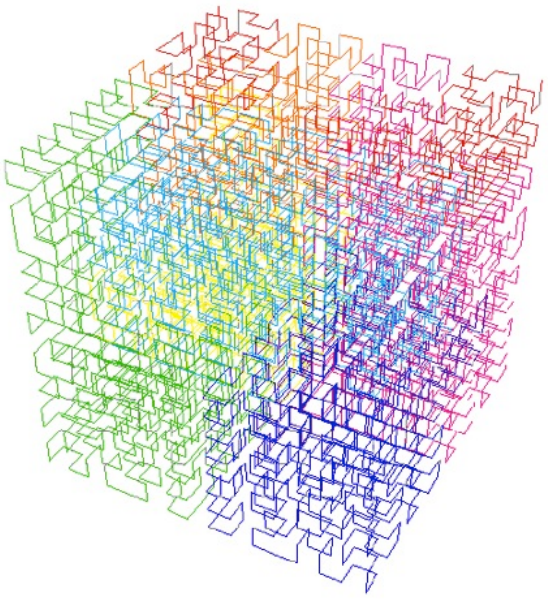


3D graphics

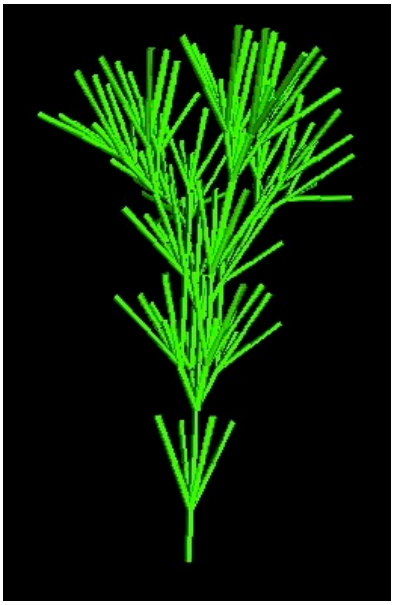
- Turtle graphics L-system interpretation can be extended to 3D space:
- Represent state as x, y, z and pitch, roll, yaw
- +, -: turn (yaw) left/right
- &, ^: pitch down/up
- \, /: roll left/right (counterclockwise/ clockwise)

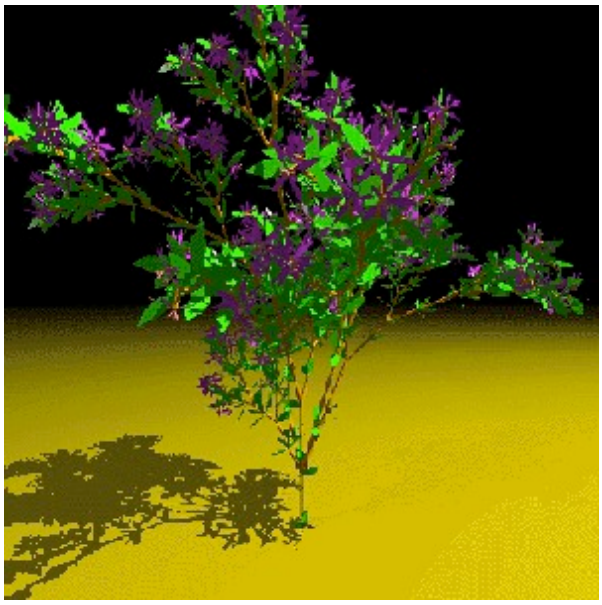
3D interpretation of L-systems





3D interpretation of bracketed L-systems





2D L-systems

Axiom: A

Rules:

A → A B / B A

B → A A / B B

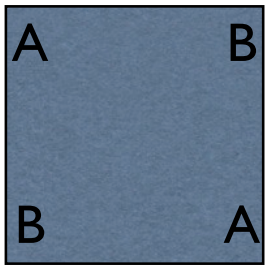
Two Expansions:

A → A B / B A

A	B	A	A
B	A	B	B
A	A	A	B
B	B	B	A

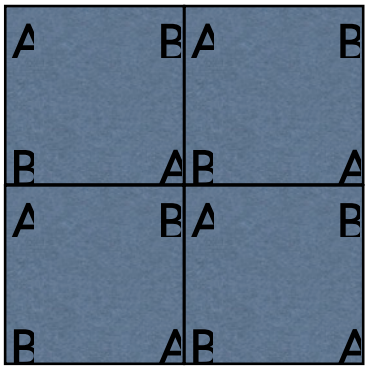
Terrain interpretation of 2D L-systems

- Each group of four letters is interpreted as instructions for lowering or raising the corners of a square
- e.g. A=+0.5, B=-0.5

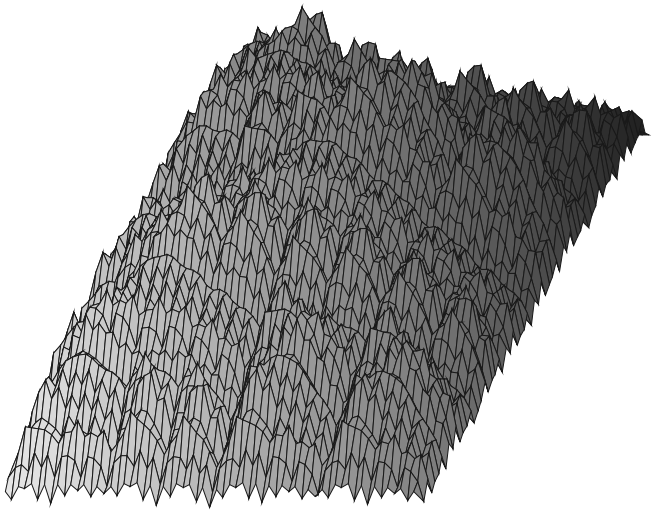


Terrain interpretation of 2D L-systems

- In next iteration, the 2D L-system is rewritten once, and each square is divided into two
- "Doubling the resolution"



Terrain interpretation of 2D L-systems



Six rewritings of A>ABBA, B>AABB

How do we design these L-systems?

Evolving L-systems

- How can we combine L-systems with evolutionary computation?

Evolving L-systems

- Evolving the axiom
- Evolving the grammar:
  - change the shape of one or more production rules, or
  - add/remove/replace productions
  - counter limits
- Evolving the interpretation:
  - Evolve production probabilities
  - Evolve other aspects (e.g. turning angles)

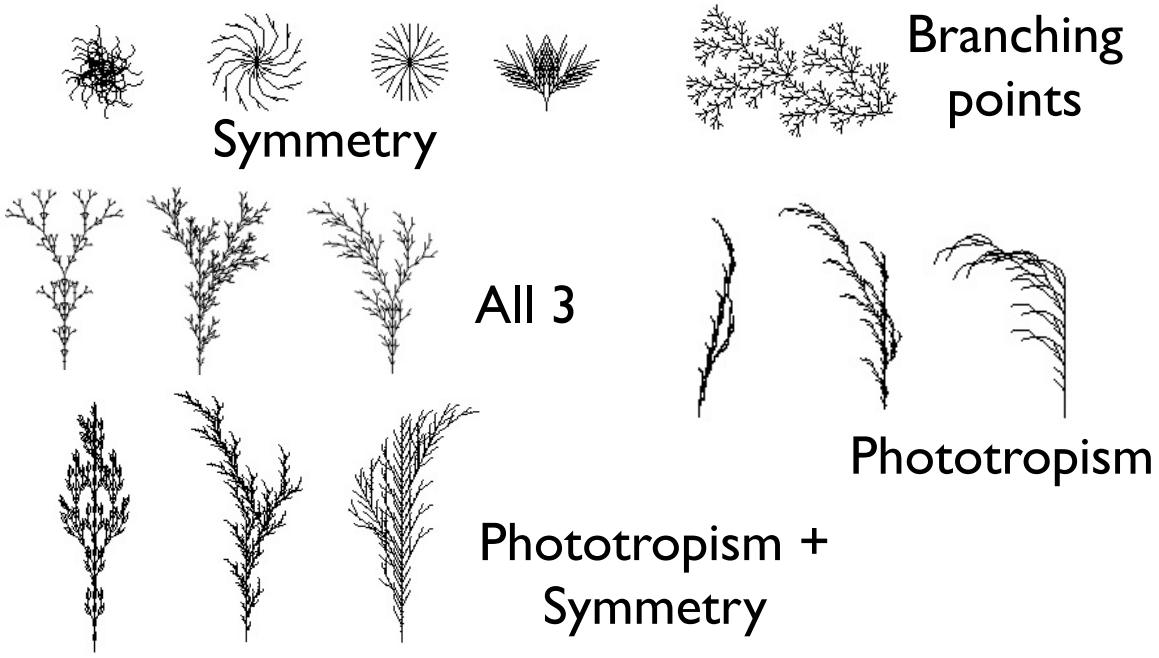
Evolving L-systems

- One example: Ochoa evolved the consequent of a single production rule
  - starting from F>F[-F]F[+F]F
- Mutation: replace single symbols, or blocks of a few symbols
- Crossover: swap complete "sub-trees" (like in genetic programming)

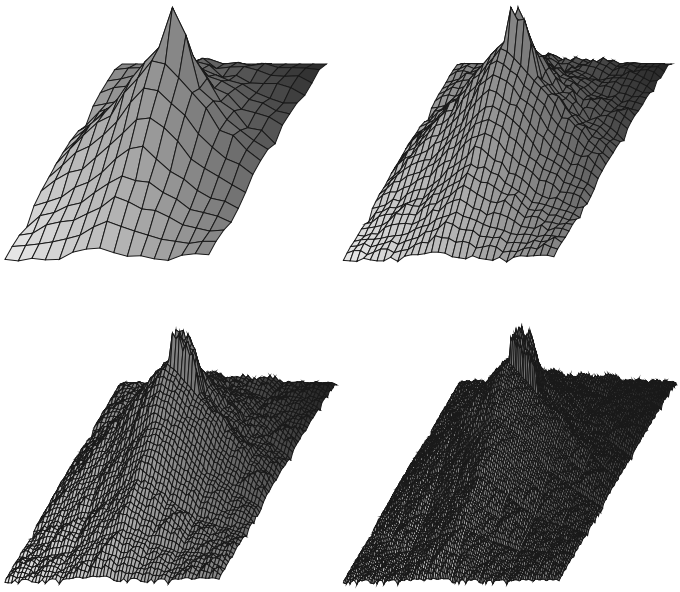
Fitness functions

- Phototropism
- Bilateral symmetry
- Proportion of branching points

Evolved L-systems

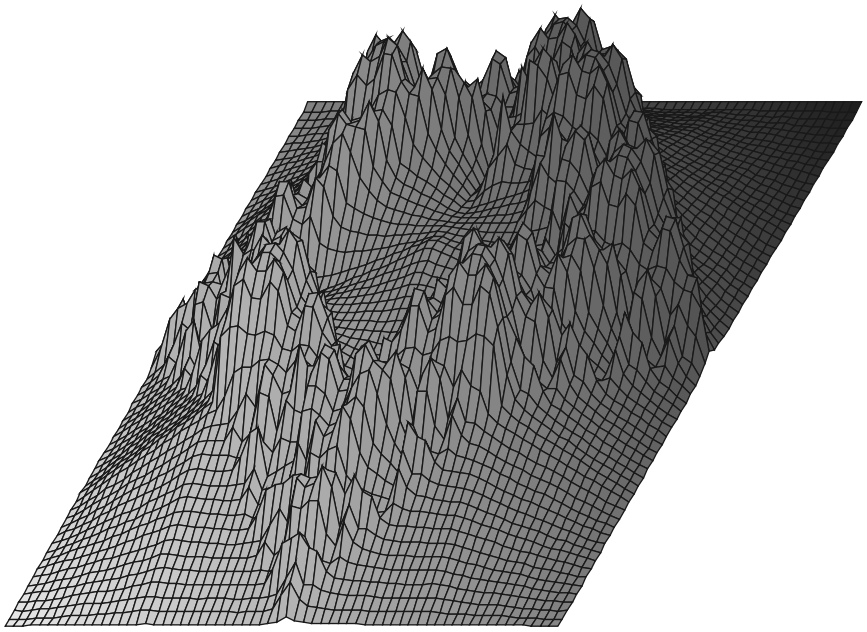


Evolved 2D L-system terrains



Very short specification, yet infinite resolution!

Evolved 2D L-system terrains



Friday, September 17, 2010

Multiobjective Exploration of the StarCraft Map Space

Julian Togelius, Mike Preuss,
Nicola Beume, Simon Wessing,
Johan Hagelbäck and Georgios N. Yannakakis

Friday, September 24, 2010

StarCraft

- Classic real-time strategy game
- Korea's unofficial national sport
- Two or three player competitive matches
- Three distinct races

Why generate maps?

- Give players an unlimited supply of new, unpredictable maps
  - Negates rote learning advantages
- Dynamically adapt the game to individual players' strengths...
  - ...or to groups of players!
- Help designers generate more novel and balanced maps
  - Help them with the "boring stuff"

Traditional (constructive) map generation

- Place features on maps according to some heuristic
  - e.g. fractals, growing islands, cellular automata
- Hard or impossible to optimize for gameplay properties
- Restrictions on possible content necessary in order to ensure valid maps

Our approach:

- Direct/indirect map representations
- An ensemble of fitness functions
- Multiobjective evolution

Our approach

- Define desirable traits of RTS maps
- Operationalize these traits as fitness functions
- Define a search space for maps
- Search for maps that satisfy the fitness functions as well as possible, using multiobjective evolution
  - (visualize trade-offs as Pareto fronts)

Desirable traits of an RTS map

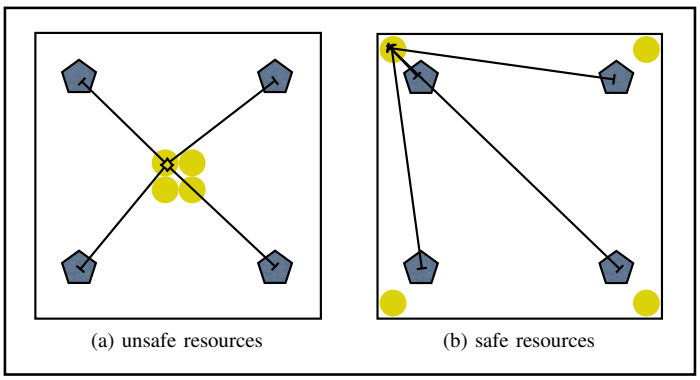
- Playability
- Fairness
- Skill differentiation
- Interestingness

Playability fitness functions

- Base space: minimum amount of space around bases
- Base distance: minimum distance between bases (via A*)

Fairness fitness functions

- Distance from base to closest resource
- Resource ownership
- Resource safety
- Resource fairness



Skill differentiation fitness functions

(also contribute to interestingness)

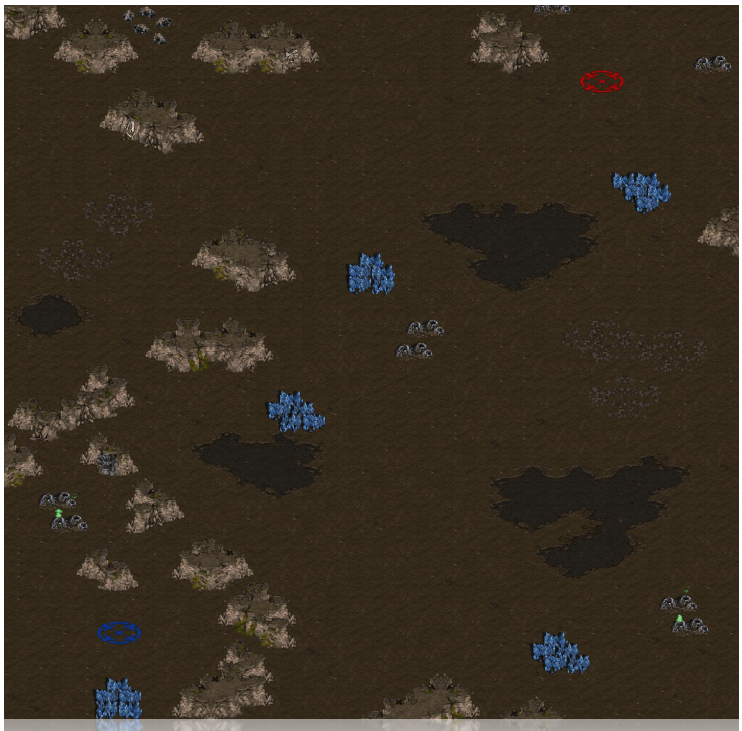
- Choke points
  (narrowest width of shortest path)
- Path overlapping

Dual map representation

- Indirect representation: a vector of real numbers in {0..1}
- Direct representation: a 64x64 grid corresponding to a StarCraft map, including impassable areas, bases, resource sites
- Genotype to phenotype mapping:
  before fitness calculation

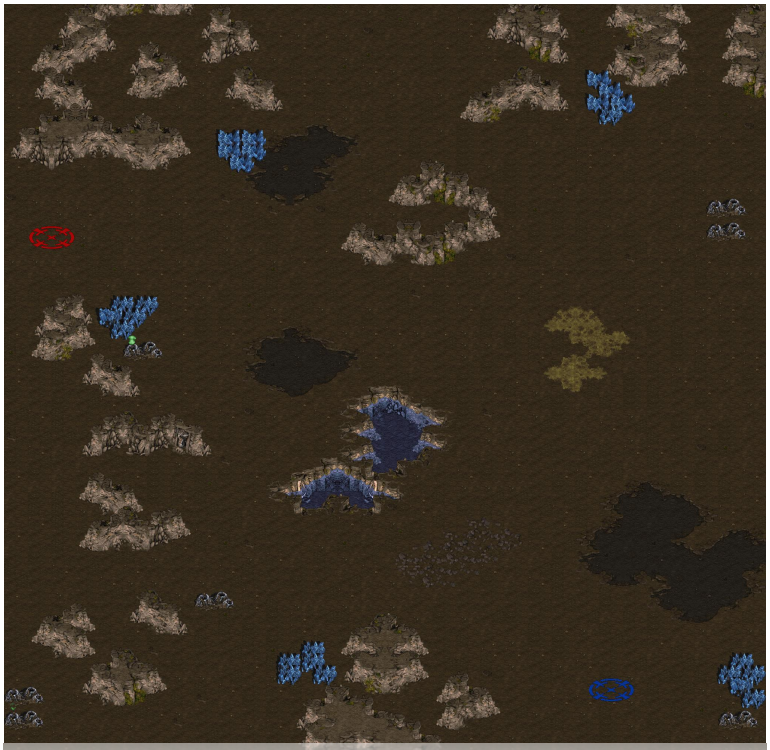
Genotype to phenotype

- Two or three bases, five mineral sources and five gas wells: *(phi, theta)* coordinates
- Rock formations represented indirectly using "turtle graphics". Each formation has:
  - *(x, y)* starting position
  - probability of turning left/right
  - probability of gaps ("lifting the pen")



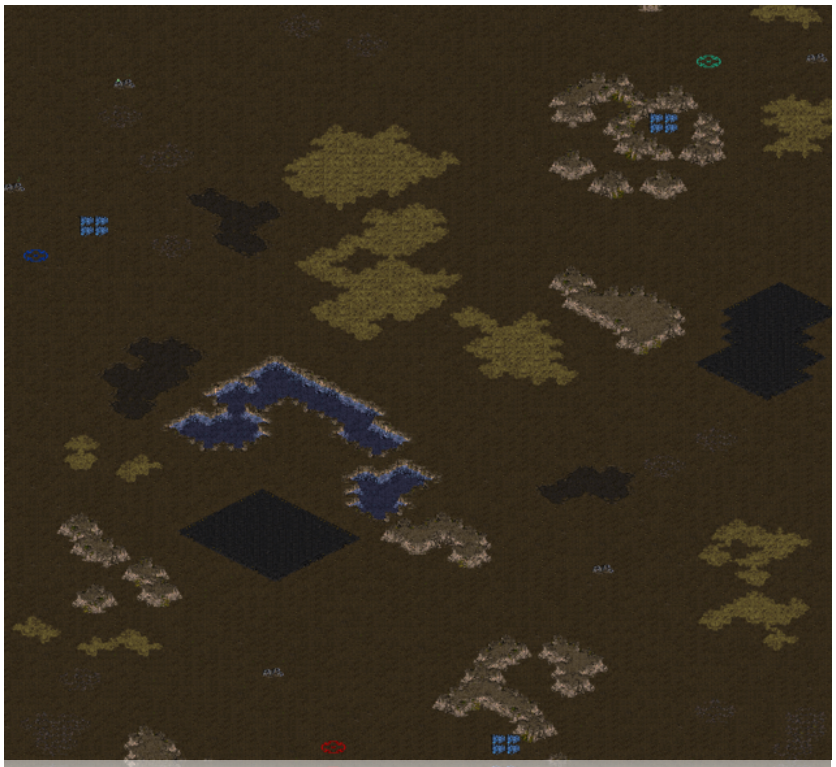
Evolved map

Resource fairness vs. choke points

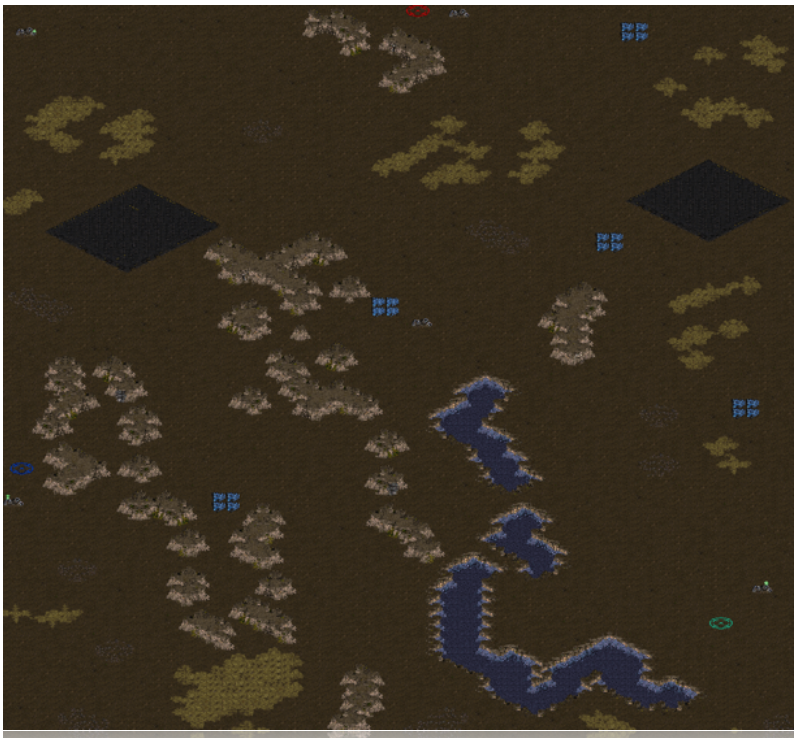


Another evolved map

Resource fairness vs. choke points



Three-player map



Another three-player map

Agent-based methods

- Use a number of "artificial agents" that construct the landscape by acting on it
- Agents of different types do different jobs
- Could be more controllable than diamond-square
- Could give rise to different types of landscapes

Controlled Procedural Terrain Generation Using Software Agents

Jonathon Doran and Ian Parberry

Published in IEEE TCIAIG, 2010

D&P's five agent types

- Coastline agents
- Smoothing agents
- Beach agents
- Mountain agents
- River agents

Rules for agents

- Each agent has a set number of "tokens" to spend on actions
- Each agent is allowed to see the current elevation around it, and allowed to modify it
- Agents don't interact *directly*

In the beginning...

...there was a vast ocean.

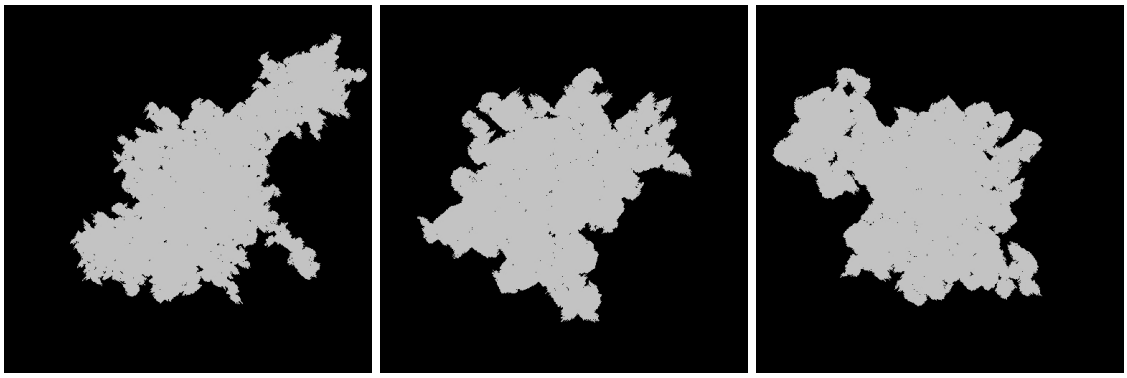
Then came the first coastline agent.

Coastline agents

- Multiply until they cover the whole coast - about 1000 necessary for this size maps
- Move out to position themselves right at the border of land and sea
- Generate a repulsor and an attractor point
- Score all neighbouring points according to distance to repulsor and attractor points
- Move to the best-scoring points, adding land as they go along


```
COASTLINE-GENERATE(agent)
 1  if tokens(agent) ≥ limit
 2     then
 3          create 2 child agents
 4          for each child
 5               do
 6                  child ← a random seed point on parent's border
 7                  child ← 1/2 of the parent's tokens
 8                  child ← a random direction
 9                  COASTLINE-GENERATE(child)
10     else
11          for each token
12               do
13                  point ← random border point
14                  for each point p adjacent to point
15                       do
16                            score p
17                  fill in the point with the highest score
```

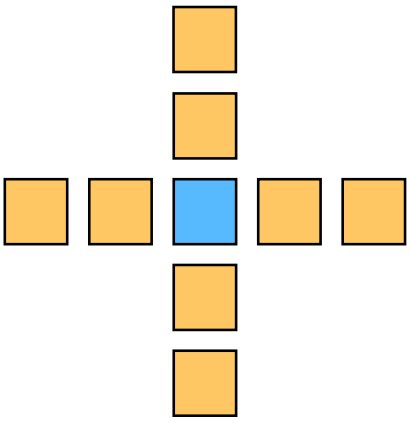
Coastline agents



Varying action sizes

Smoothing agents

- Take random walks on the map
- Change the elevation of each visited point to (almost) the mean of its extended von Neumann neighbourhood



Smoothing agents

```
SMOOTH(starting-point)
1  location ← starting-point
2  for each token
3       do
4          height_location ← weighted average of neighborhood
5          location ← random neighboring point
```

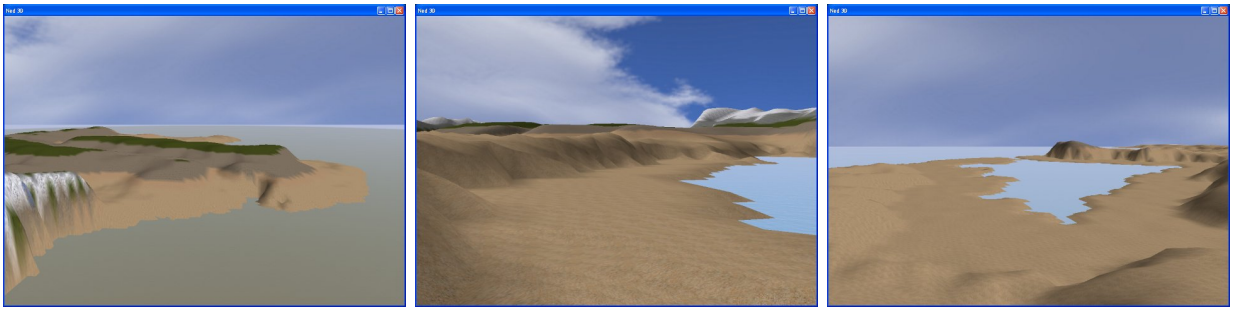

Beach agents

- Select random position along the coast, where coast is not too steep
- Flatten an area around this point (leaving small variations)
- Move randomly a short direction away from the coast, flattening the area

Beach agents

```
BEACH-GENERATE(starting-point)
 1  location ← starting-point
 2  for each token
 3        do
 4           if height_location ≥ limit
 5              then
 6                   location ← random shoreline point
 7           flatten area around location
 8           smooth area around location
 9           inland ← random point a short distance inland from location
10           for i ← 0 to size(walk)
11                 do
12                    flatten area around inland
13                    smooth area around inland
14                    inland ← random neighboring point
15           location ← random neighboring point of location
```


Beach agents



Varying beach width

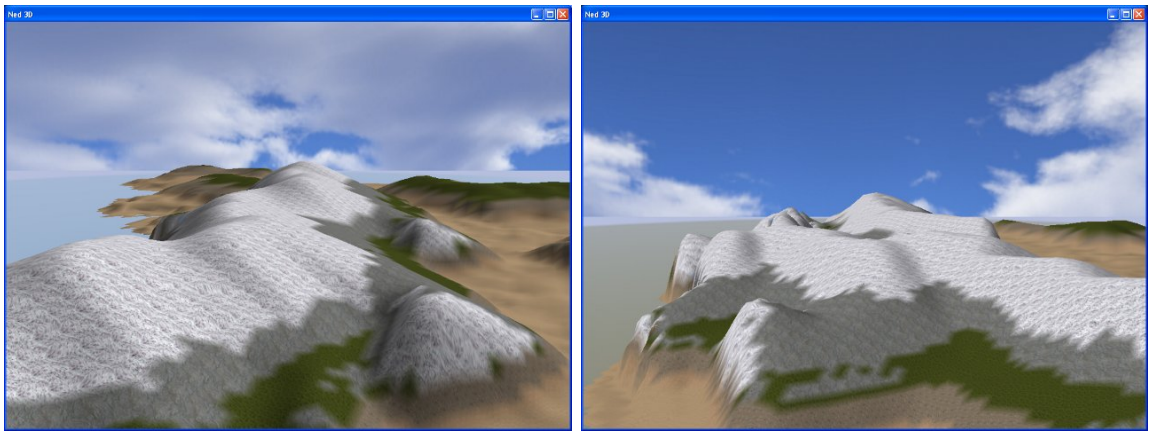
Mountain agents

- Start at random positions and directions
- Move forward, continuously elevating a wedge, creating a ridge
- Turn randomly without 45 degrees from the initial course
- Periodically offshoot "foothills" perpendicular to movement direction

Mountain agents

```
MOUNTAIN-GENERATE(starting_point)
 1  location ← starting-point
 2  direction ← random direction
 3  for each token
 4       do
 5          elevate wedge perpendicular to direction
 6          smooth area around location
 7          location ← next point in direction
 8          every n-th token
 9               do
10                  direction ← original-direction ± 45-degrees
```

Mountain agents



Narrow versus wide features

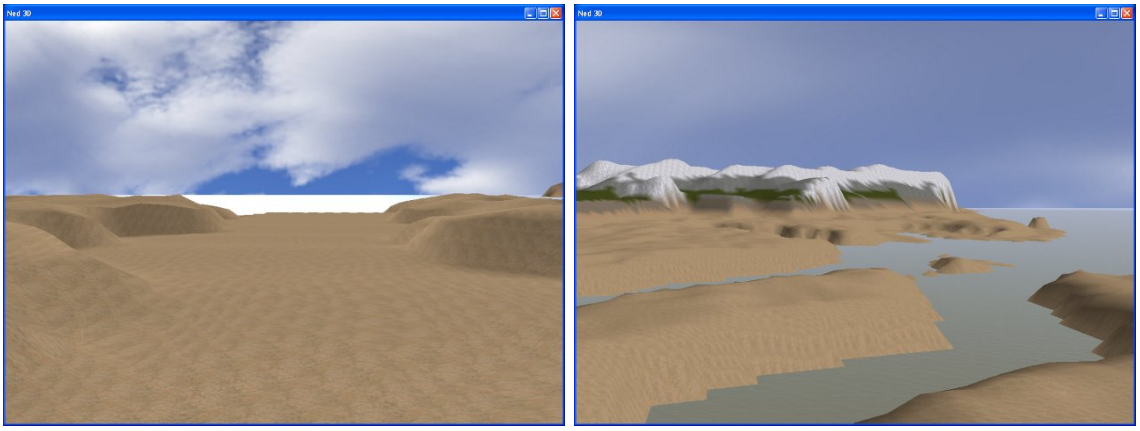
River agents

- Move from a random point on the coast towards a random point on a mountain ridge
- "Wiggle" along the path
- Stop when reaching too high altitudes
- Retrace the path down to the ocean, deepening a wedge along the path

River agents

```
RIVER-GENERATE()
 1  coast ← random point on coastline
 2  mountain ← random point at base of a mountain
 3  point ← coast
 4  while point not at mountain
 5        do
 6           add point to path
 7           point ← next point closer to mountain
 8  while point not at coast
 9        do
10           flatten wedge perpendicular to downhill direction
11           smooth area around point
12           point ← next point in path
```


River agents



A dry river, and the outflow of three rivers

In what order?

- Doran and Parberry suggest
  - Coastline
  - Landform
  - Erosion
- But the "Implementation" suggests random order

Further questions

- Parameters... what parameters?
- What features of landscapes do we want to be able to specify?
- How can the human and the algorithm interact productively?

Lecture 6:
Rules and mechanics

Procedural Content Generation, Autumn 2010

Julian Togelius

Salen and Zimmermann define games:

"A game is a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome"

Rules? Mechanics?

- Salen and Zimmermann: three levels of rules
- *Operational:* the explicit instructions, e.g. on the box of a board game, or the range of options available to players in a digital game.
- *Constitutive*: underlying formal structures beneath the game. E.g. code.
- *Implicit*: social rules around the game and what it is to play it. Usually not specified.

Can we create game rules automatically?

- If so, which types of rules?
- For which types of games?
- How would we represent them?
- How would we judge how good a set of rules is?
- And why would we do this?

Challenges

- How to represent game mechanics
  - Representation should be complete
  - Most games should make sense (?)
  - High locality (?)
  - Human-readable/editable (?)
- How to search the space
- How to evaluate the games

Automatic generation of recombination games

Cameron Browne

PhD Thesis, 2008
IEEE TCIAIG, 2010

“Combinatorial games”

- Finite: produce a well-defined outcome.
- Discrete: turn-based.
- Deterministic: chance plays no part.
- Perfect information: no hidden information.
- Two-player.

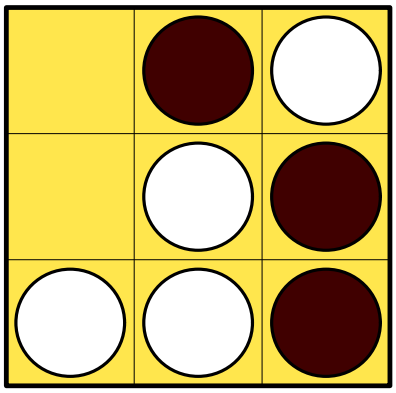
The Ludi Game Description Language

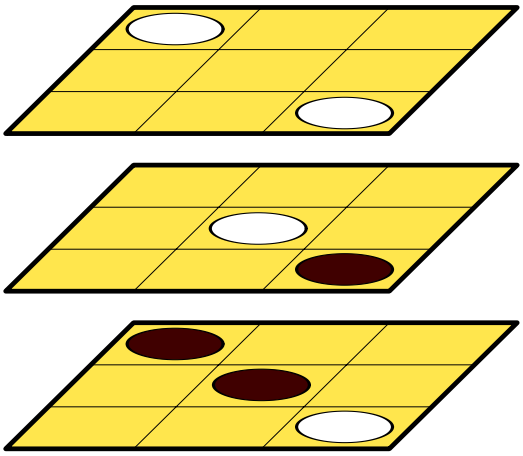
- In practice limited to board games
- *Ludeme:* Fundamental units of independently transferable game information (“game meme”)
  - (tiling square)
  - (size 3 3)

Tic-Tac-Toe

```
(game Tic-Tac-Toe
  (players White Black)
  (board
    (tiling square i-nbors)
    (size 3 3)
  )
  (end (All win (in-a-row 3)))
)
```


(size 3 3) vs (size 3 3 3)





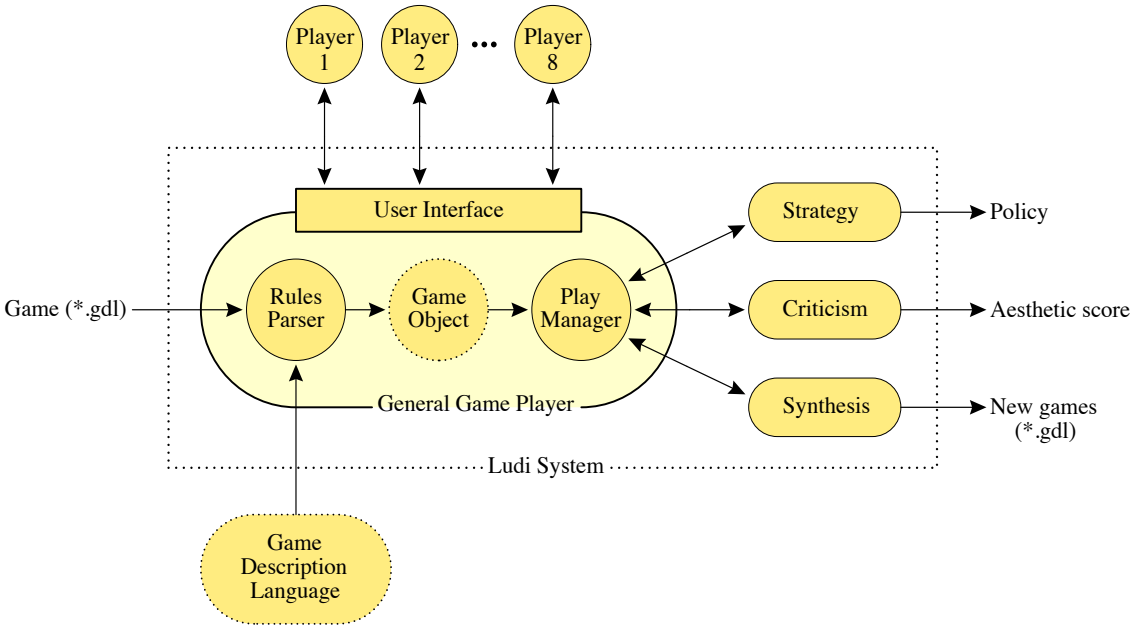
Similar Game Description Languages

- Zillions of Games ZRF
  - More general than the Ludi GDL, but still limited
  - Hierarchical, human-readable
- Stanford GDL
  - Based on first-order logic
  - Quite general, but still limited to discrete, perfect information games

Playing an arbitrary game

- Play the game using standard Alpha-Beta search (with various additions)
  - Needs a board state evaluation function!
- Twenty different *advisors* provide various assessments of a particular board state
- For each game, the linear combination of these advisors into a value is optimized using an ES

The *Ludi* system



Evaluating a game

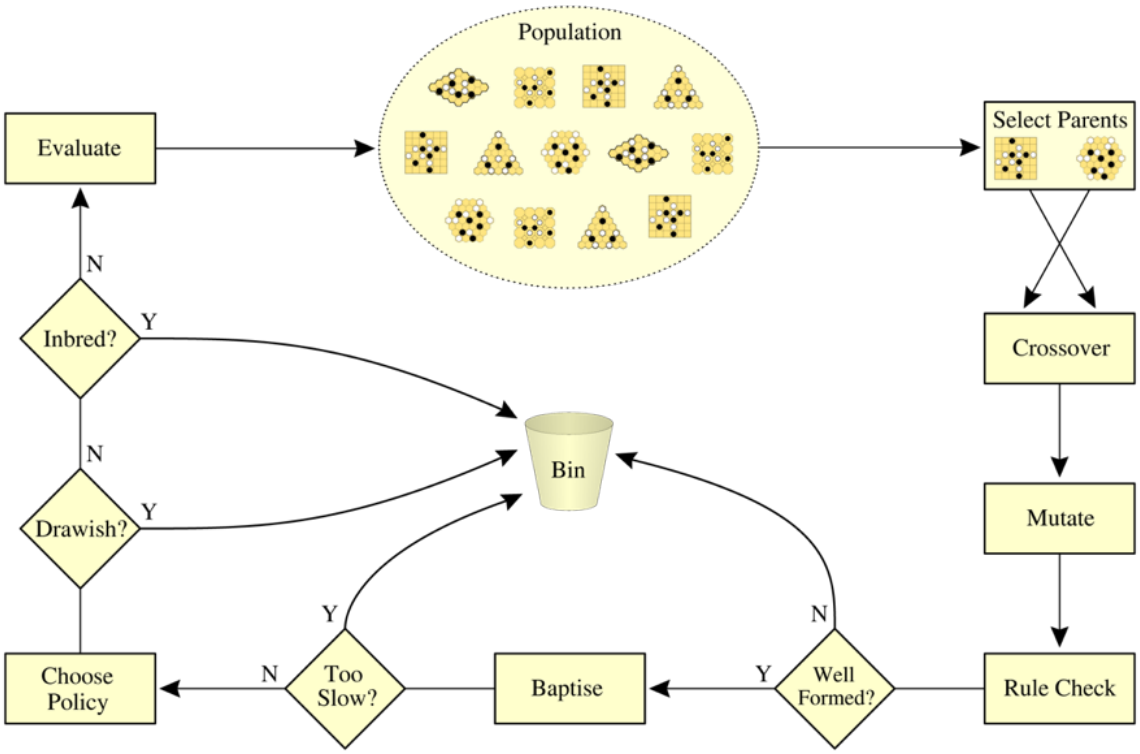
- Play the game (both player use same algorithm, with optimized board evaluation)
- Measure various *aesthetic criteria*: aspects of how the game is played, of the ruleset, and of the outcomes
- Combine the scores into a fitness value somehow

Aesthetic criteria

- 16 Intrinsic: based on rules and equipment
- 11 Viability: based on game outcomes
  - e.g. completion, duration
- 30 Quality: based on trends in play
  - e.g. drama, uncertainty

Combining the criteria

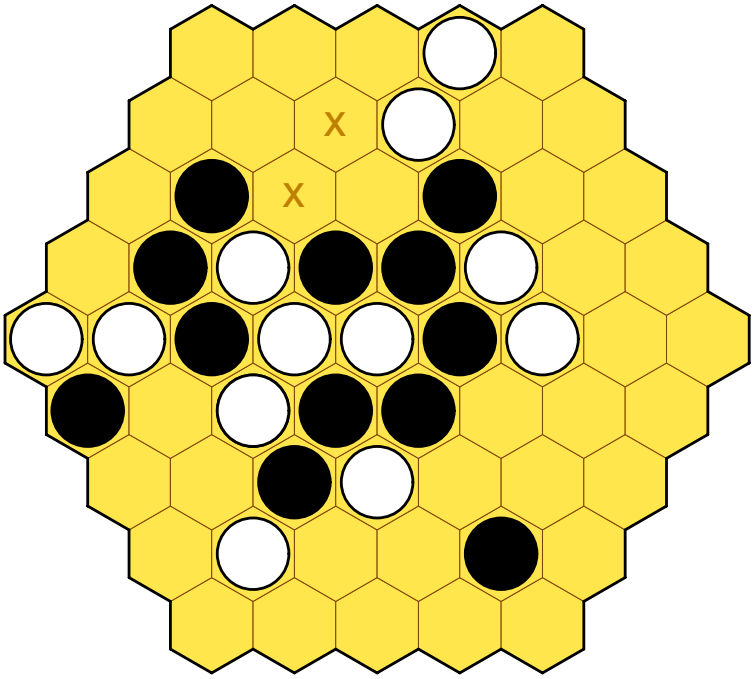
- The 57 criteria need to be weighted into a single fitness value
- Weighting was established through first scoring 79 sample games
- Then letting human players play (some of) and rank the same games
- Fitting the weight vector using cross-entropy



Yavalath

```
(game Yavalath
  (players White Black)
  (board (tiling hex) (shape hex) (size 5))
  (end
    (All win (in-a-row 4))
    (All lose (and (in-a-row 3) (not (in-a-row 4))))
  )
)
```

Yavalath



Friday, October 8, 2010

Combining human and computer creativity

Procedural Content Generation, Autumn 2010

Julian Togelius

Who creates a game's content?

- The designer(s)/developer(s)?
- A computer-implemented algorithm?
- The players?

Player-created worlds

PCG and authorship

- How can we combine a human designer's authorial control and expressive ability with PCG capabilities?
- Dimensions of control
- Ease of use
- Multi-level editing / two-way flow of control

"But game designers are experts..."

- Possible to use != easy and efficient to use
- Prototyping
- End users: Game players, educators, trainers
- Other development professions: managers, programmers etc.

Combining PCG techniques

- To build a complete game/world, we need different types of content, designed by or with different algorithms
- Problems:
  - Differing data structures
  - One-way flow of control
  - Interface constraints

Integrating procedural generation and manual editing of virtual worlds

Ruben Smelik, Tim Tutenel,
Klaas Jan de Kraker and Rafael Bidarra

FDG Workshop on PCG, 2010

Sketchaworld framework

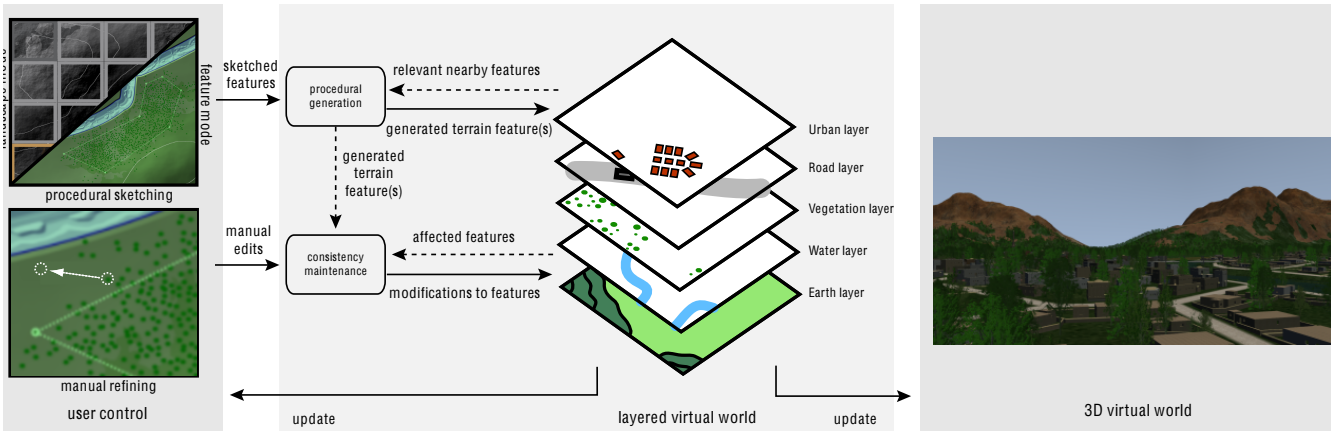
Goals:

- Increase designers' productivity while retaining creative control
- Provide intuitive way of working with PCG algorithms for non-experts
- Provide framework in which to integrate new PCG research

Declarative modelling

- Designers state their *intent* (what they want) instead of *method* (how to get it)
- Procedural sketching: "paint" with PCG tools
- Consistency maintenance through a GIS-inspired system of layers

Declarative modelling



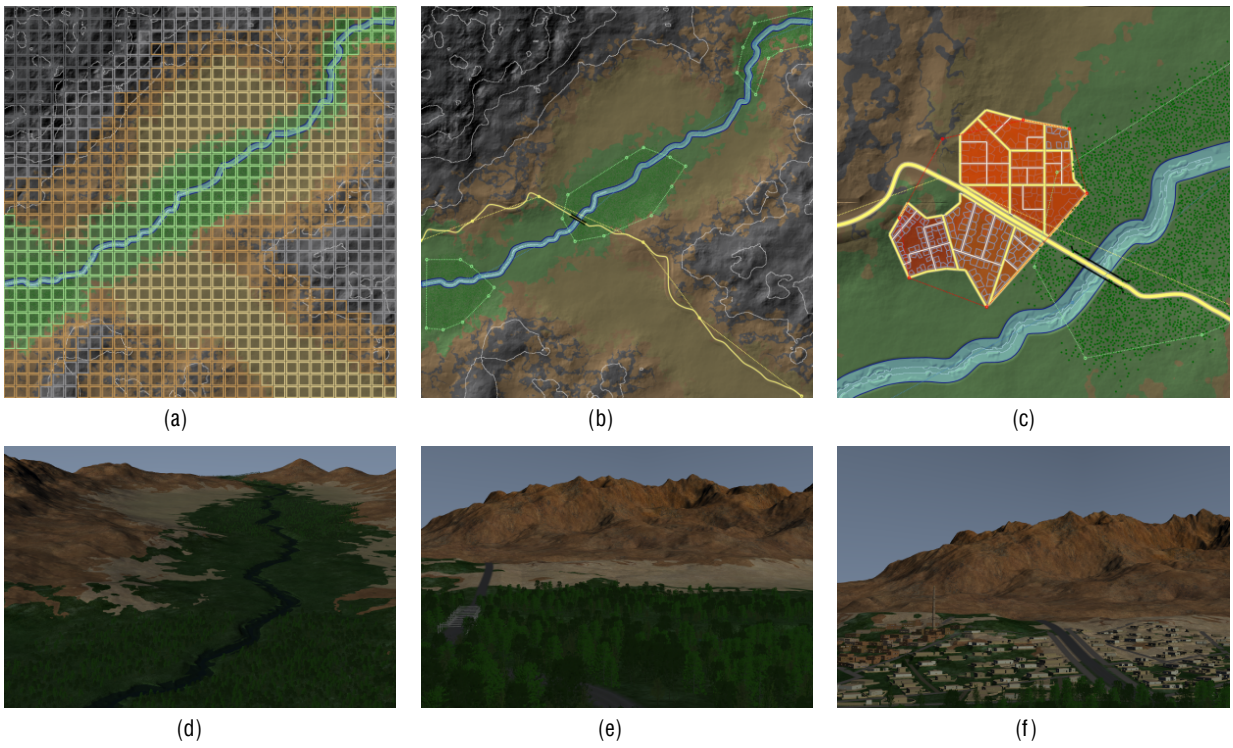


Figure 2: Results of an example procedural sketching session: a) sketch of a natural environment b) road sketched through the valley from east to south, crossing the river c) city outlined on a hill d) resulting natural landscape e) river crossing with bridge f) resulting city on the hills.

Manual editing

- Coarse level: mountain ranges, rivers, cities. Heavily dependent on procedural generation.
- Medium level: city districts, parks, roads. Procedural generation useful.
- Fine level: individual objects (houses, trees). Little or no procedural generation.
- Micro level: meshes, textures

Open issues

- Preserving manual changes
- Balance control and consistency
- Iterative modeling workflow and edit history (recreate previous actions?)

the death of level designer

seriously ?

Runtime random level generation

- What is missing?
  - Creating fully 3D world spaces, including bridges, archways, towers,..

Design of Level Content

- PCG is used as a mechanism for minimizing the cost of content creation.
- Only? Any other reasons?

Dynamic World Generation

- Used when in-game map exceeds the ability of the computer to store it.
- Use a constant seed number.
- Impossible to implement roads and rivers
  - Why not?

Procedural Puzzle and Plot-generation

- Prevents the user from getting the information off from a game FAQ
- Gives infinite number of ways of solving a puzzle
- Non-linear sandbox design

Procedural Content Generation in Games

- Is the programmatic generation of game content using a random or pseudo-random process that results in an unpredictable range of possible game play spaces.
- Any limitations above?

Where PCG will move?

- Traditional level design will adopt more PCG functions
- Games that do PCG will do much better in the marketplace
- PCG will continue to eat away at the bottom end
- Middleware developers will get on board with PCG

Where PCG will move?

- The real strength of PCG will be seen in procedural generation of plot and narrative content
- The greatest challenge of PCG will be to augment or replace human intelligence in the creation of meaningful narrative
- The one area that random map generation is missing is complex 3D topology generation