Procedural Content Generation

Artificial Intelligence for
Interactive Media and Games

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[Based on lecture by Julian Togelius, IT University of Copenhagen]]

What is PCG in games?

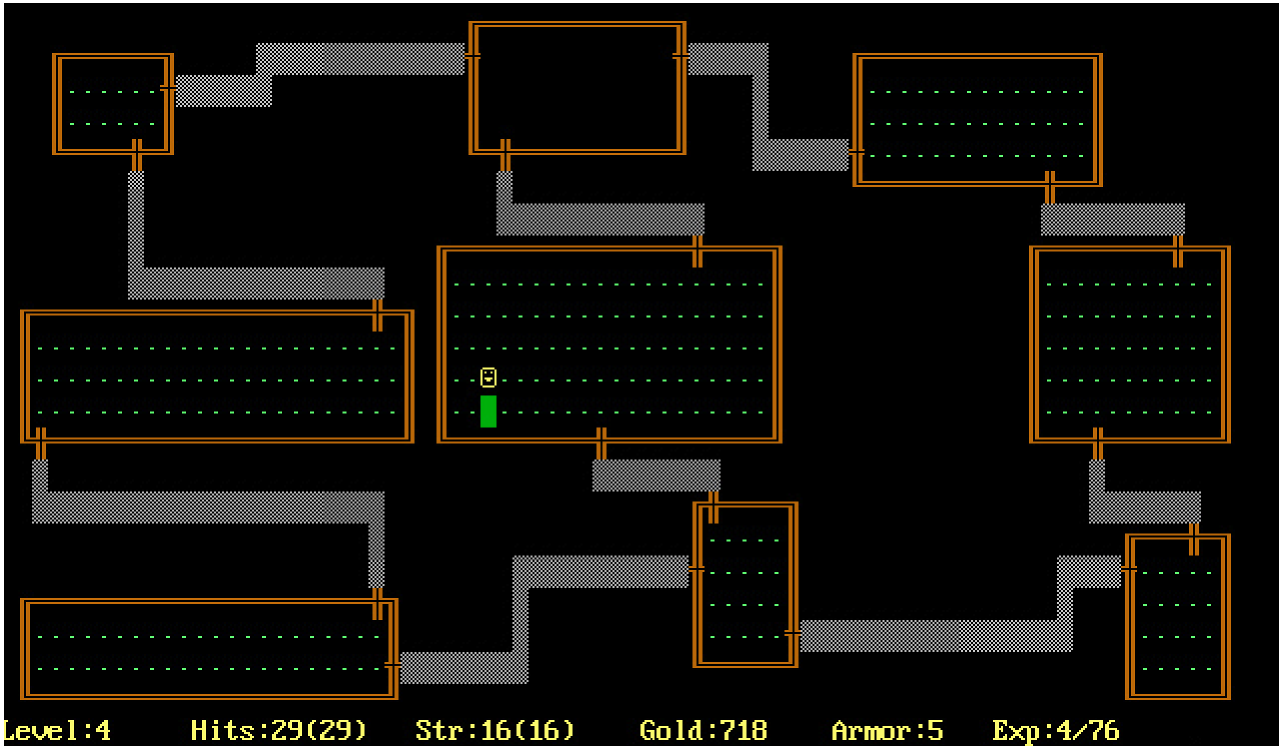
- Procedural Generation: with no or limited human intervention, algorithmically
- of Content: *not* NPC behaviour, *not* the game engine, things that affect gameplay
- in Games: computer games, board games... any kind of games

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

- Tribal Trouble

2005

Civilization IV

2005

History: Runtime random level generation

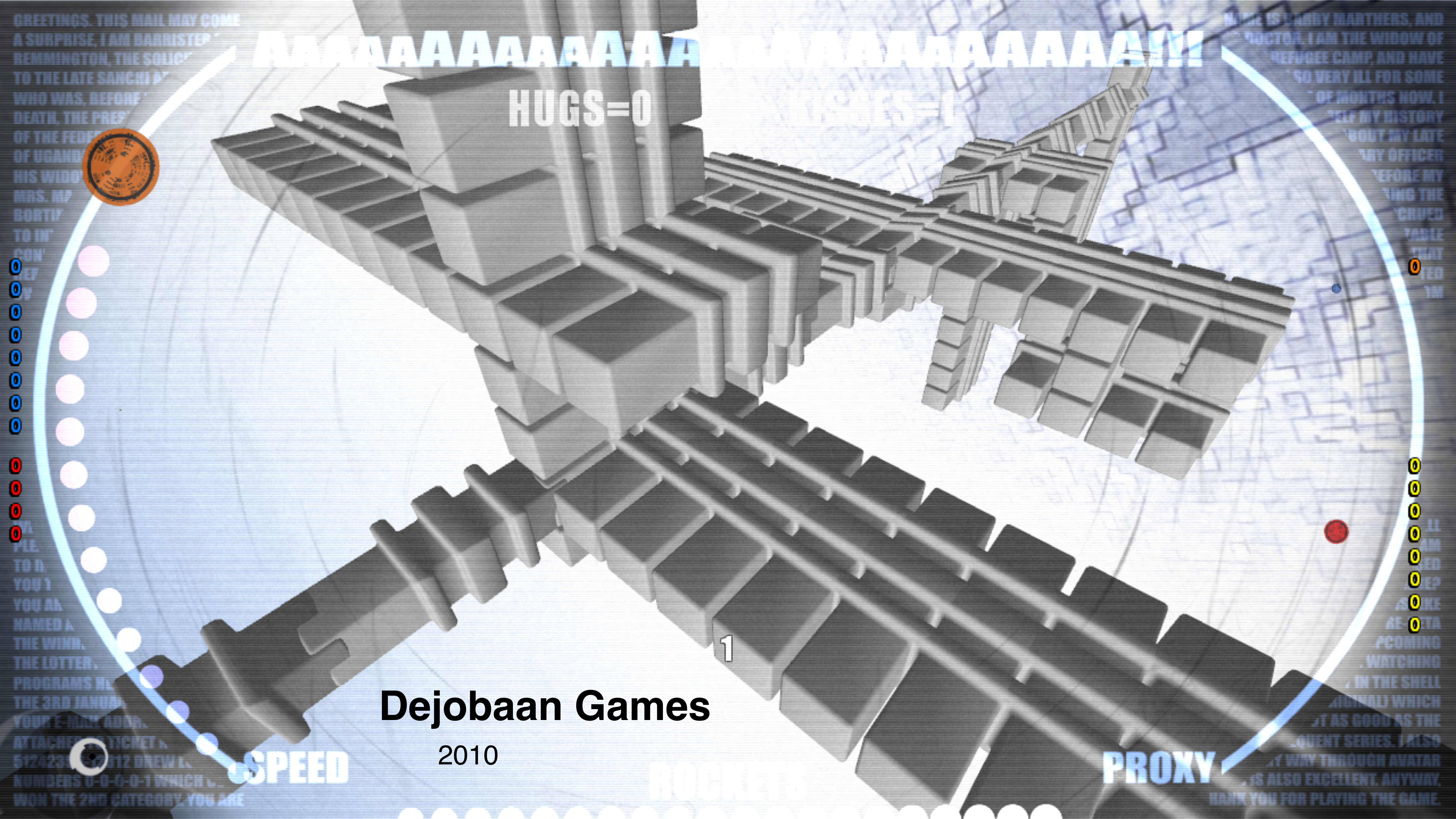
- Dwarf Fortress-3D

2007

Diablo


LEVEL UP
CHAR
QUESTS
MAP
MENU
INV
SPELLS
GHOUL
TOTAL KILLS : 25
IMMUNE : MAGIC

2008



Dejobaan Games

2010

SpeedTree


KFS1
WEAPON
19 : 5
INFANTRY
F1 - mission
F2 - target
F3 - brigade
F4
F5
F6 - help
clear, cpdump, cpinfo, crs, defend, fbs, find, friends, gm, gmmode, grab, gridsnapshot, hc, hclist, hcmotd, hcoff, hcon, help, home, hqoff, hqon, ignore, kick, kickall, kickban, lastcap, lastdeaths, lastmoves, listsquad, liststos, m, makeco, makeleader, mlist, movebrigade , movedivision, msp, noechat, nowho, nukepersonas, objectives, orders, overrun, own, pinfo, pwncp, rebuildcp, renamesquad, report, resetstrat, resync, roster, setmotd, setrank, shutdown, snoop, spam, status, sys, sysmotd, time, trainers, um, ungrab, voteco, voting, warn, warnall, whisper, who, wtf, yell

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

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

KFS1
WEAPON
19 : 5
INFANTRY
F1 - mission
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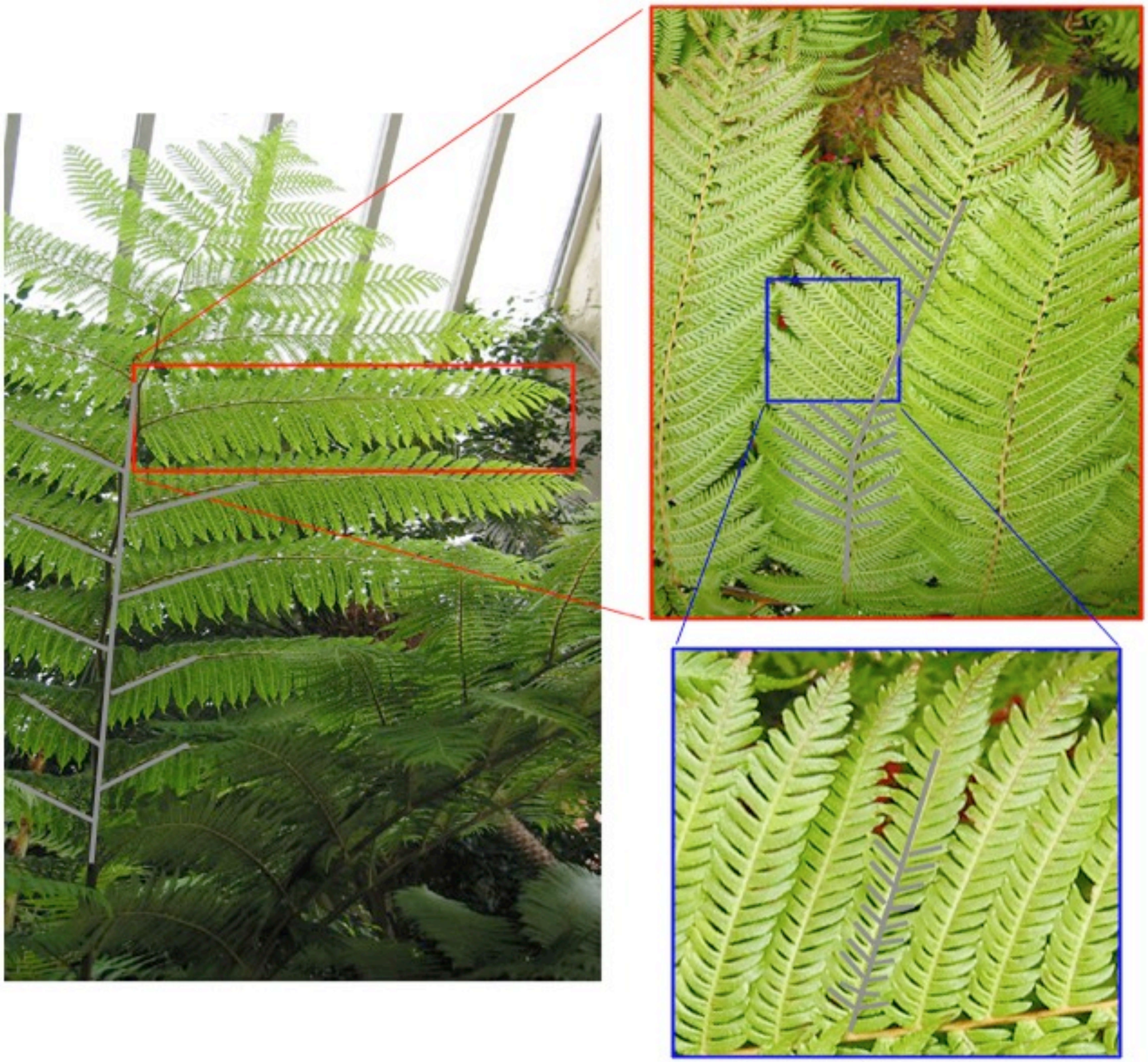
clear, cpdump, cpinfo, crs, defend, fbs, find, friends, gm, gmmode, grab, gridsnapshot, hc, hclist, hcmotd, hcoff, hcon, help, home, hqoff, hqon, ignore, kick, kickall, kickban, lastcap, lastdeaths, lastmoves, listsquad, liststos, m, makeco, makeleader, mlist, movebrigade , movedivision, msp, noechat, nowho, nukepersonas, objectives, orders, overrun, own, pinfo, pwncp, rebuildcp, renamesquad, report, resetstrat, resync, roster, setmotd, setrank, shutdown, snoop, spam, status, sys, sysmotd, time, trainers, um, ungrab, voteco, voting, warn, warnall, whisper, who, wtf, yell

Self-similarity



Self-similarity

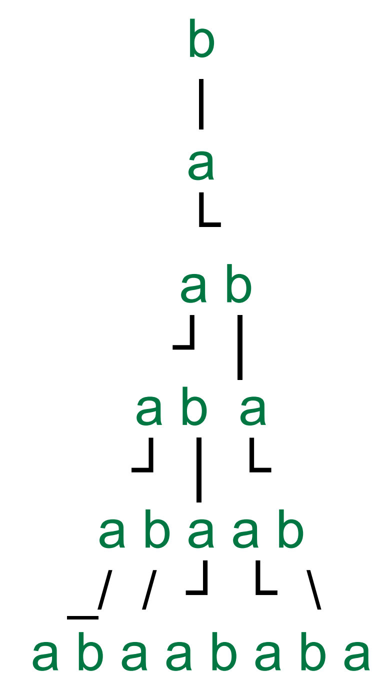
- Nature has obviously thought out some clever way of representing complex organisms using a compact description...
- ...permitting individual variation...
- ...why is this relevant for us?

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

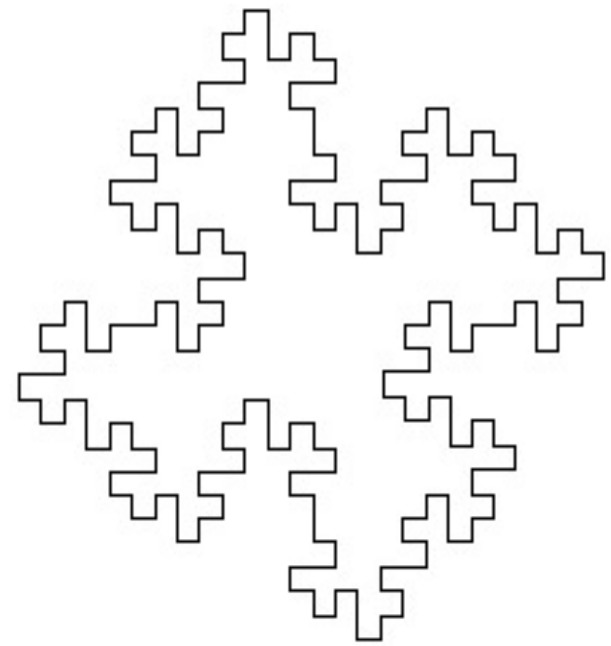
- Invented/popularized by Prusinkiewicz 1986
- Core idea: interpret generated strings as instructions for a turtle in turtle graphics
- Read the string from left to right, changing the state of the turtle (x, y, heading)

Example graphical L-system

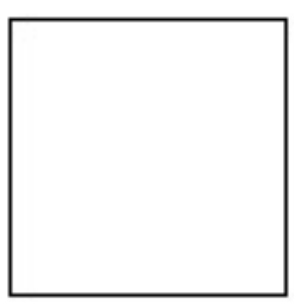
- Alphabet: {F, f, +, -}
- F: move the turtle forward (drawing a line)
- f: move the turtle forward (don't draw)
- +/-: turn right/left (by some angle)

Graphical L-system

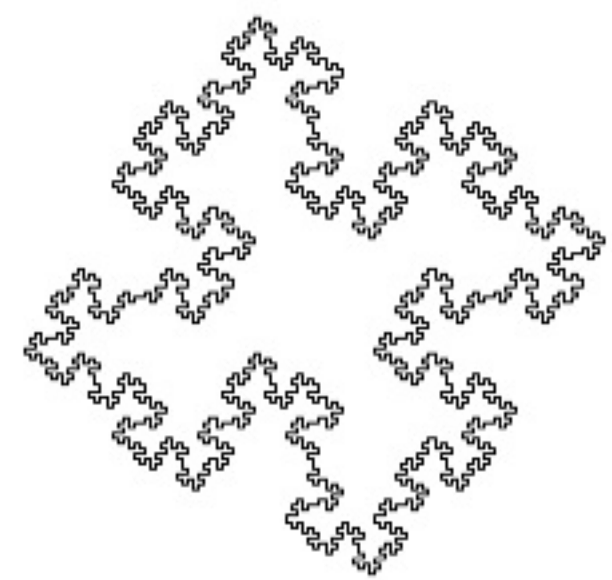
- axiom: F+F+F+F
- grammar: F>F+F-F-FF+F+F-F
- Turning angle: 90°



n=1



n=0



n=2

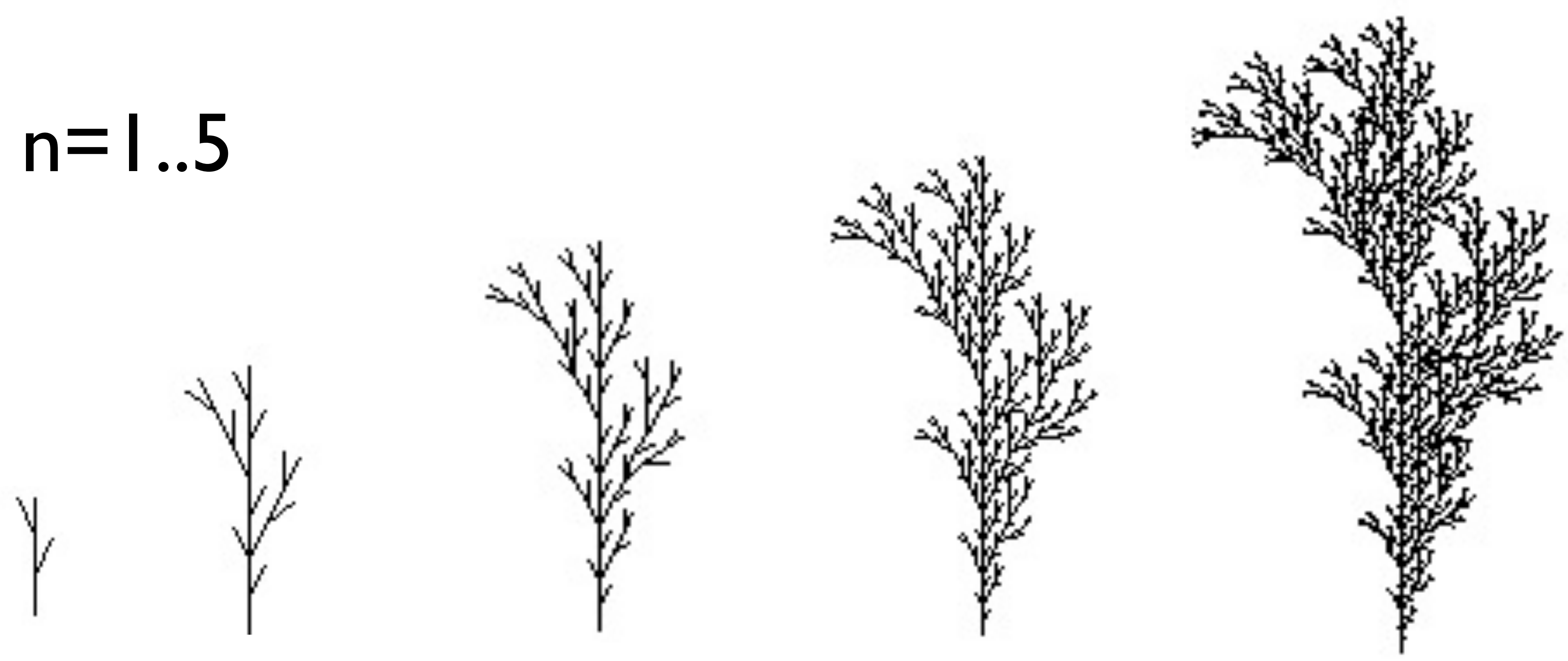
Bracketed L-systems

- 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°

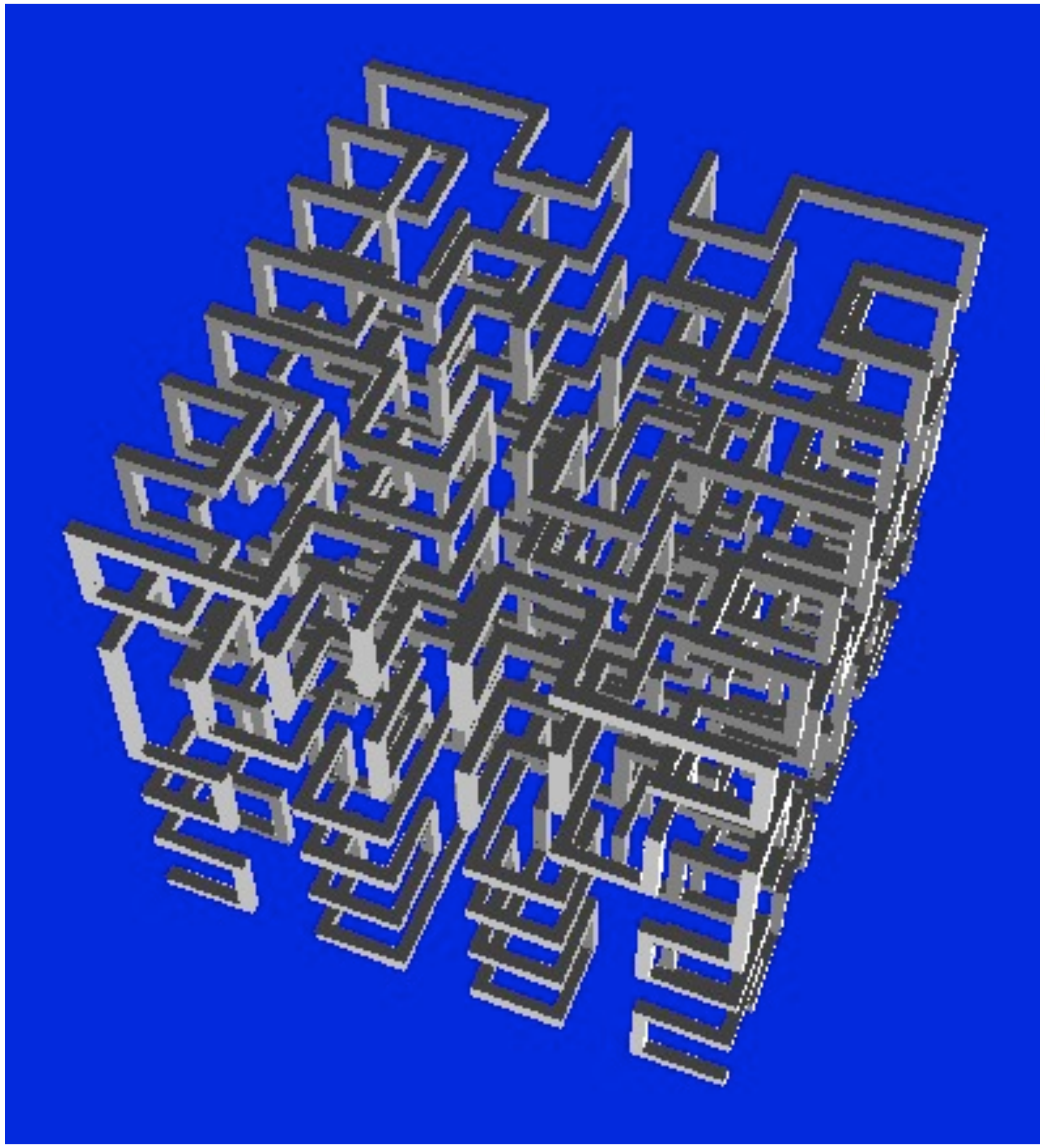
n=1..5

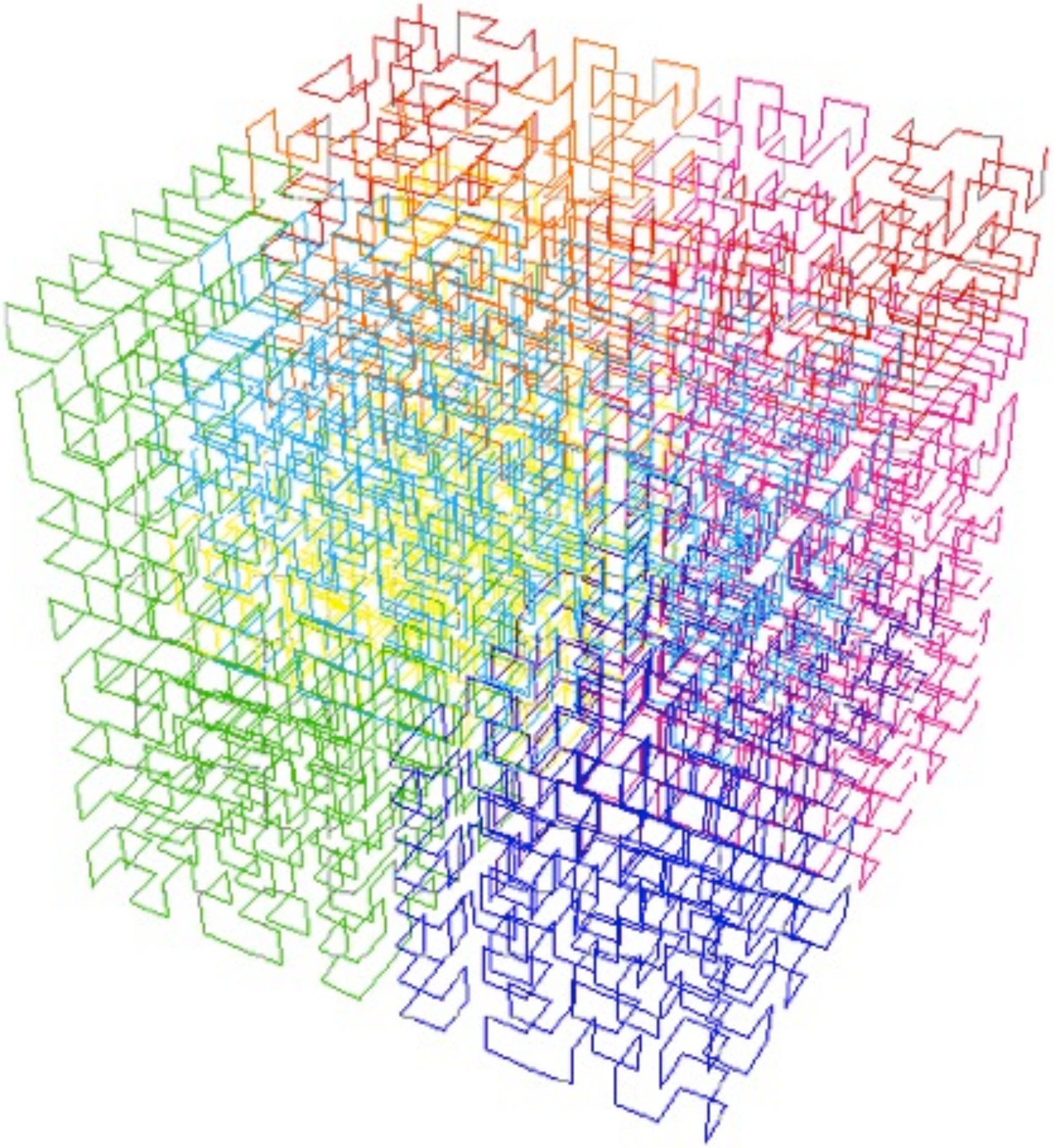


3D graphics

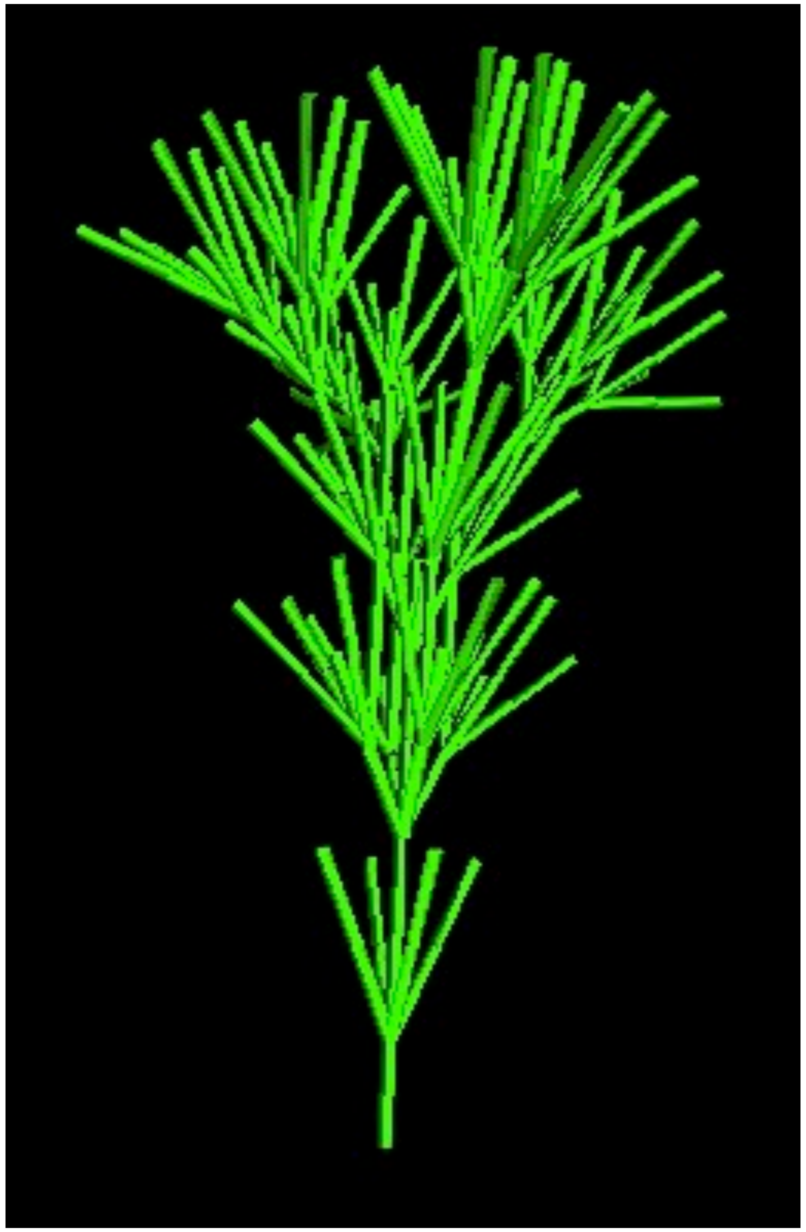
- Turtle graphics L-system interpretation can be extended to 3D space:
- Represent state as x, y, z and pitch, roll, yaw
- +, -: turn (yaw) left/right
- &, ^: pitch down/up
- \, /: roll left/right (counterclockwise/ clockwise)

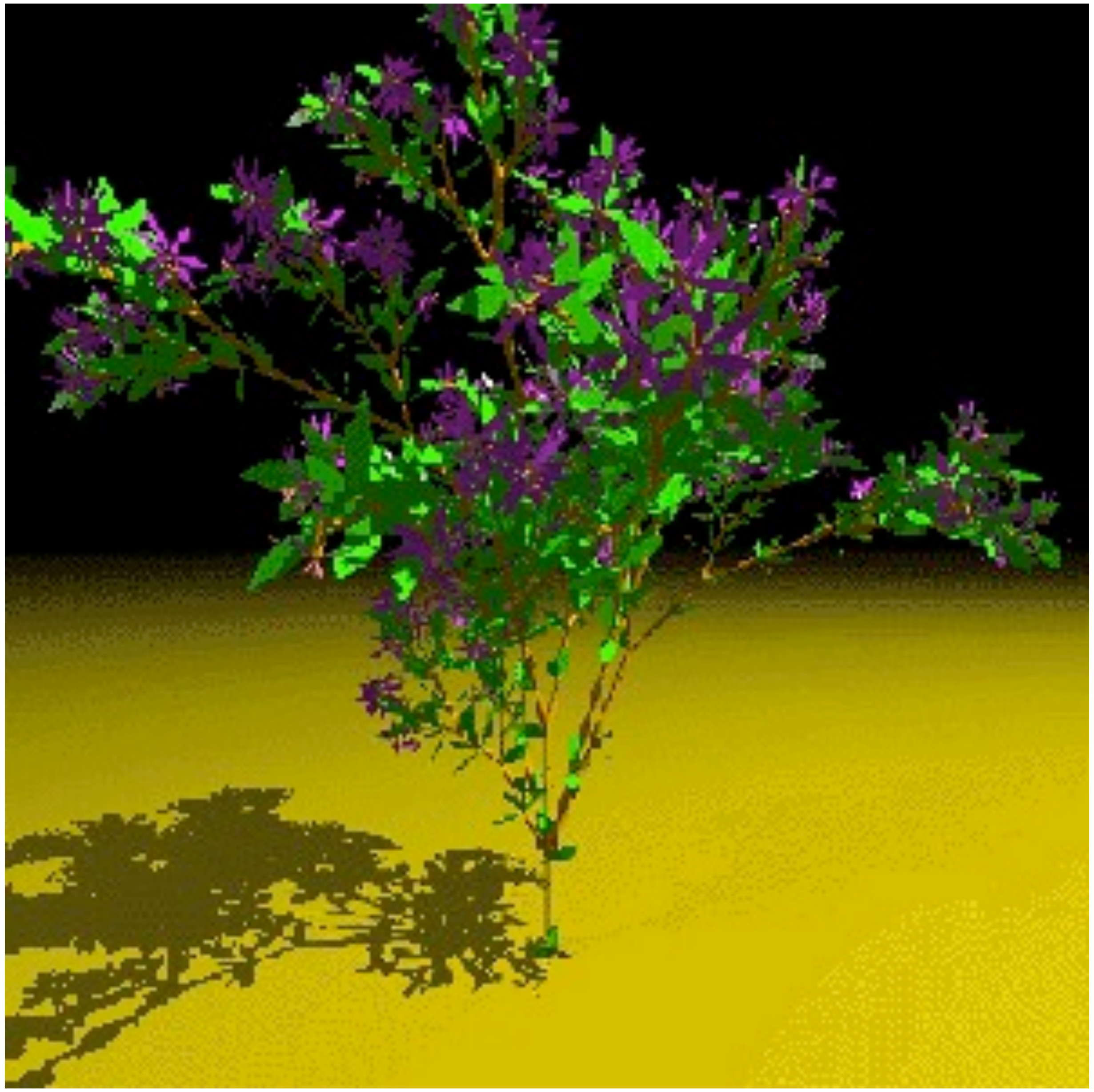
3D interpretation of L-systems



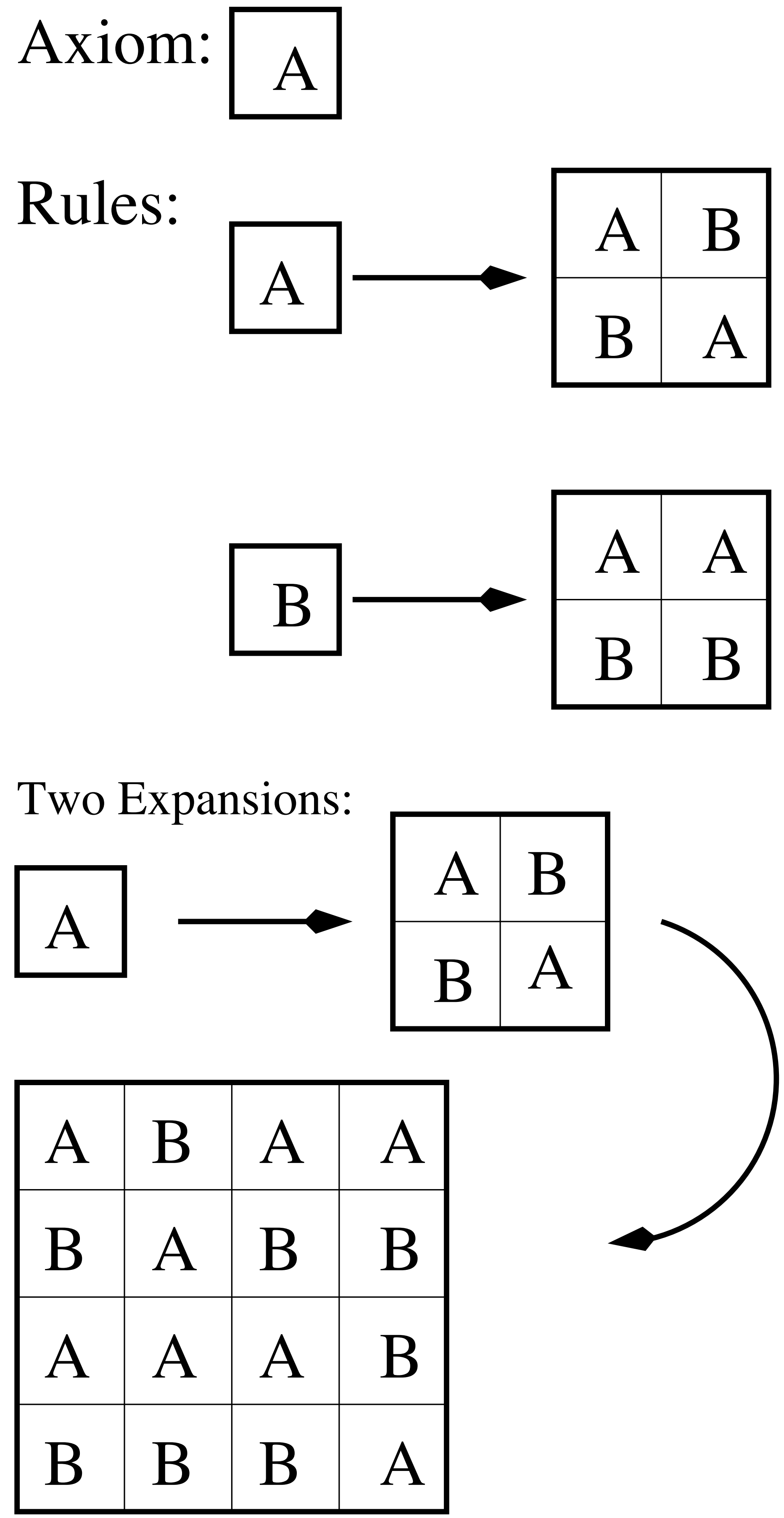


3D interpretation of bracketed L-systems



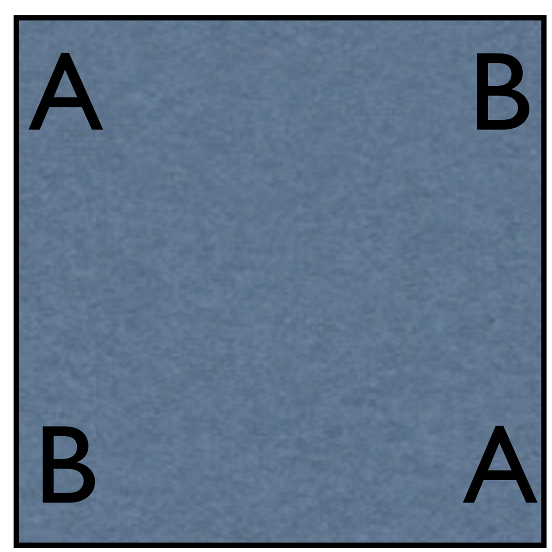


2D L-systems


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

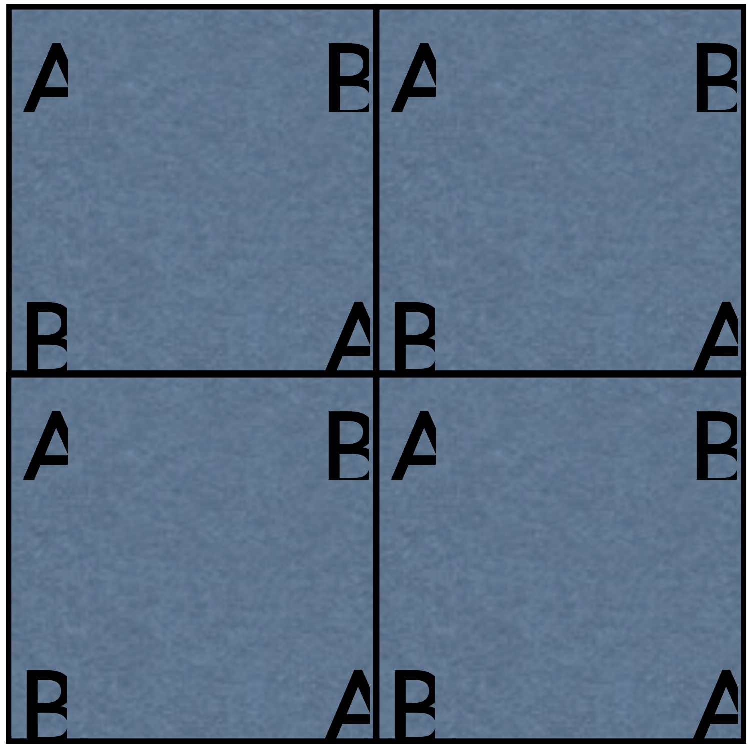
Terrain interpretation of 2D L-systems

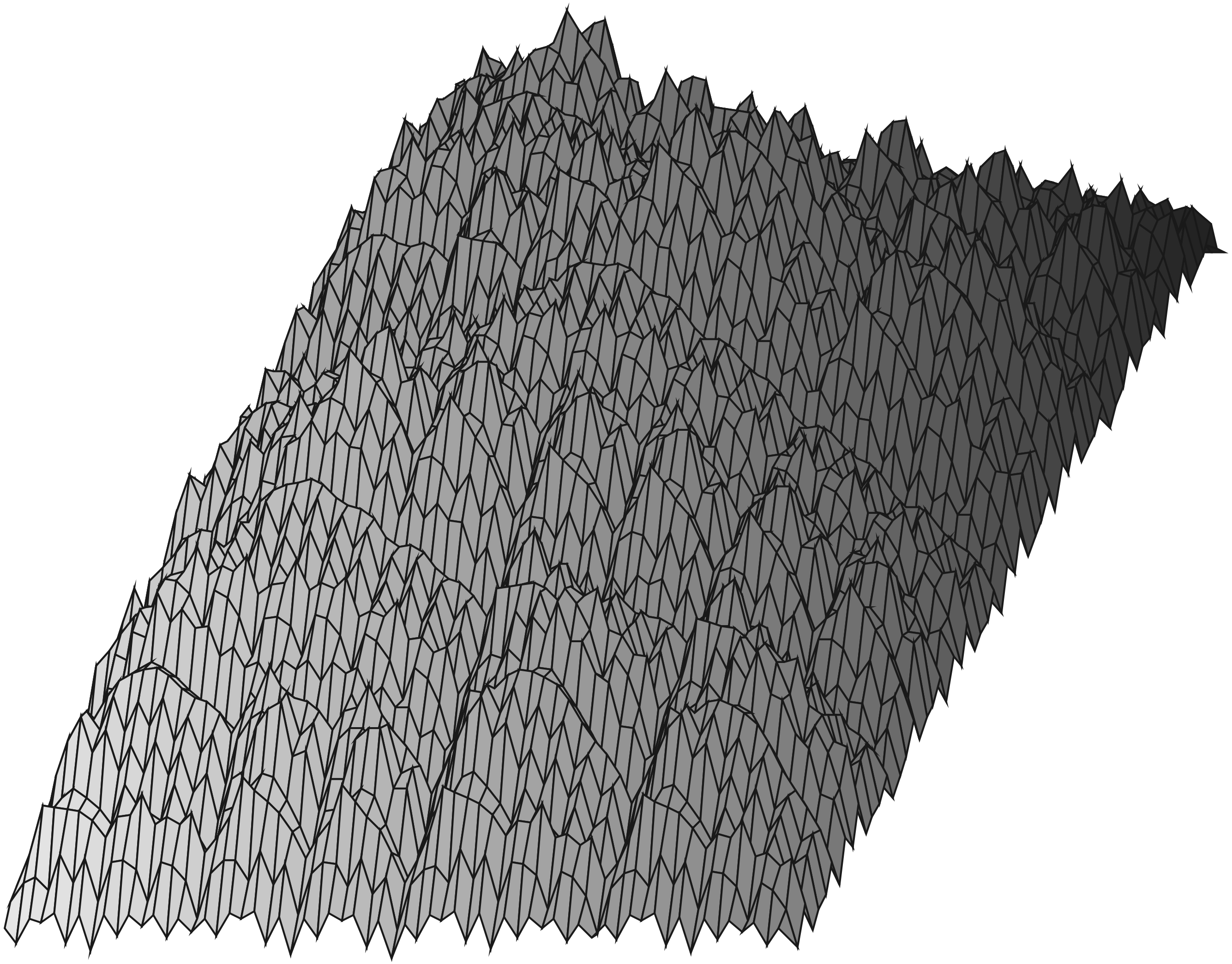
- Each group of four letters is interpreted as instructions for lowering or raising the corners of a square
- e.g. A=+0.5, B=-0.5



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”





Evolving L-systems

- How can we combine L-systems with 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

Evolving L-systems

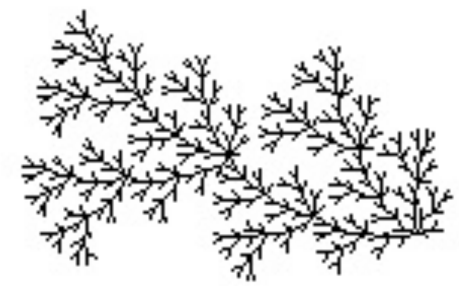
- Evolving the axiom
- Evolving the grammar:
  - change the shape of one or more production rules, or
  - add/remove/replace productions
  - counter limits
- Evolving the interpretation:
  - Evolve production probabilities
  - Evolve other aspects (e.g. turning angles)

Fitness functions

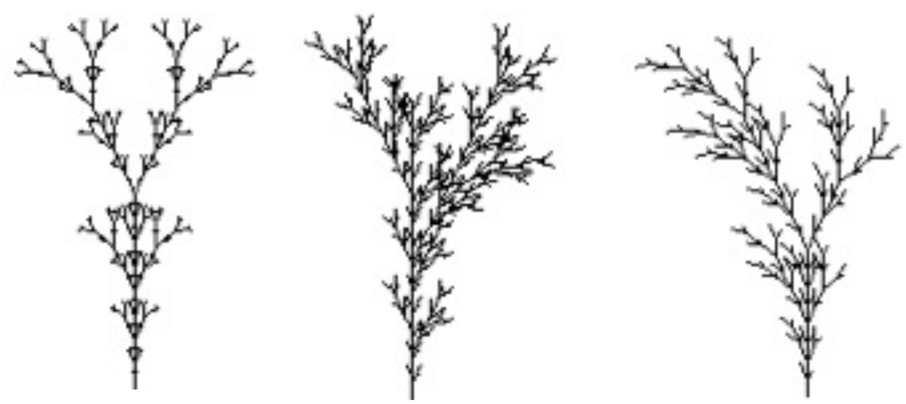
- Phototropism
- Bilateral symmetry
- Proportion of branching points

Evolved L-systems

Symmetry

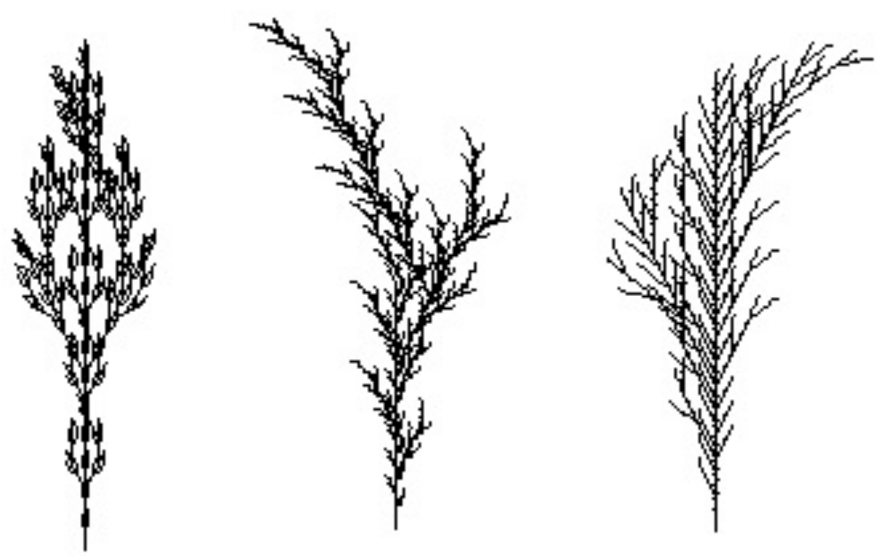


Branching points



All 3

Phototropism



Phototropism + Symmetry

Multiobjective Exploration of the StarCraft Map Space

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

2010 IEEE Symposium on Computational Intelligence and Games

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

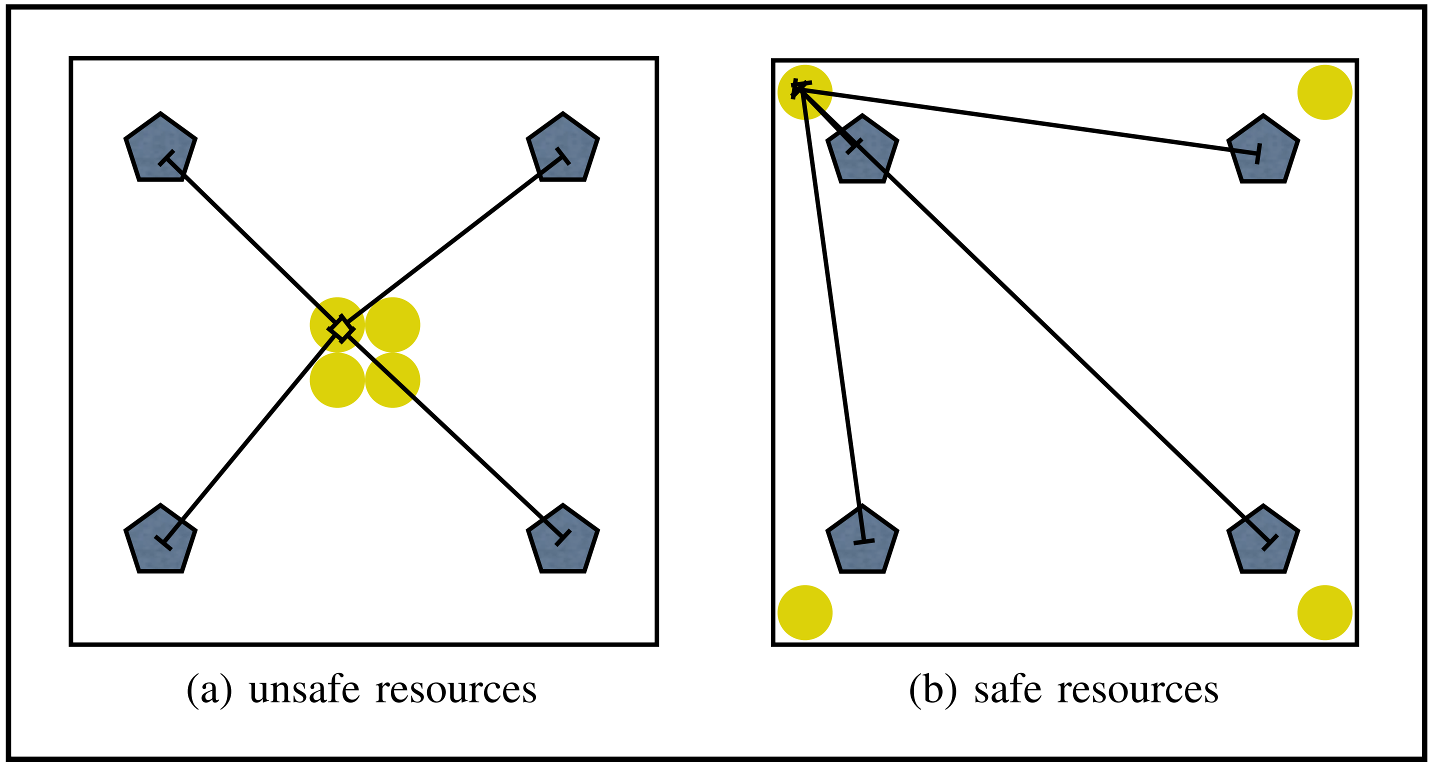
- Playability
- Fairness
- Skill differentiation
- Interestingness

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)

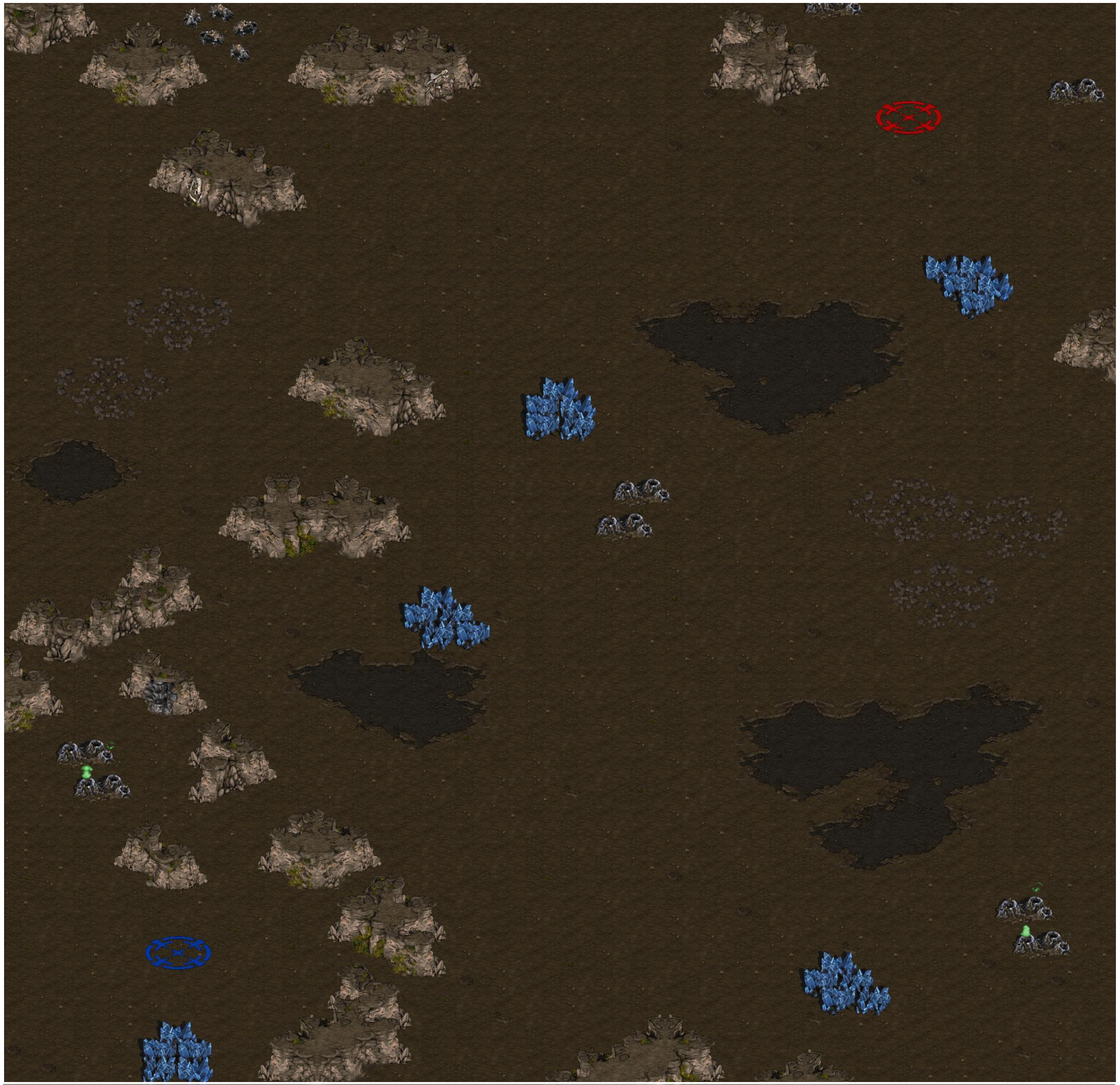
- Choke points
  (narrowest width of shortest path)
- Path overlapping

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

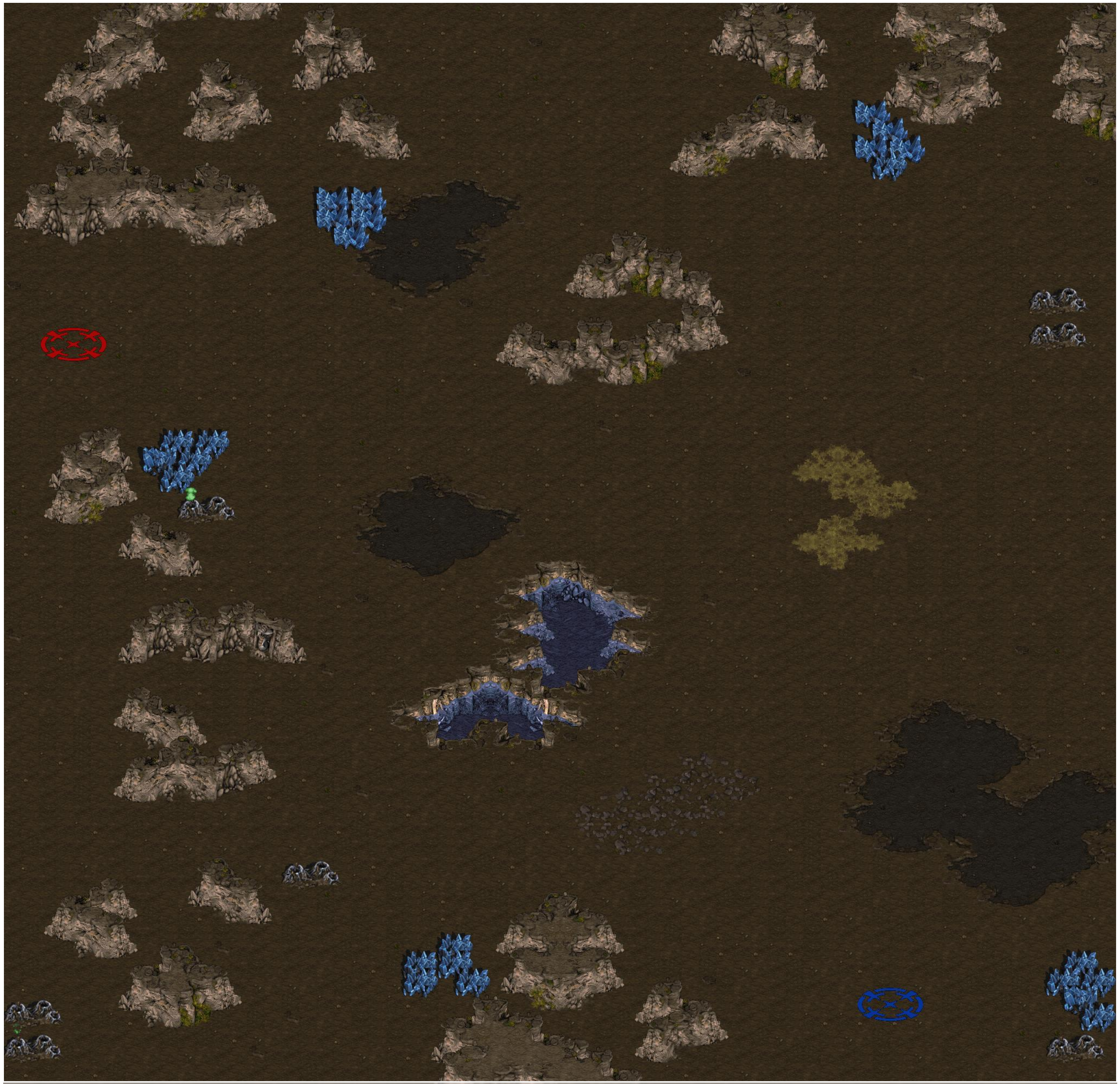
Genotype to phenotype

- 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")



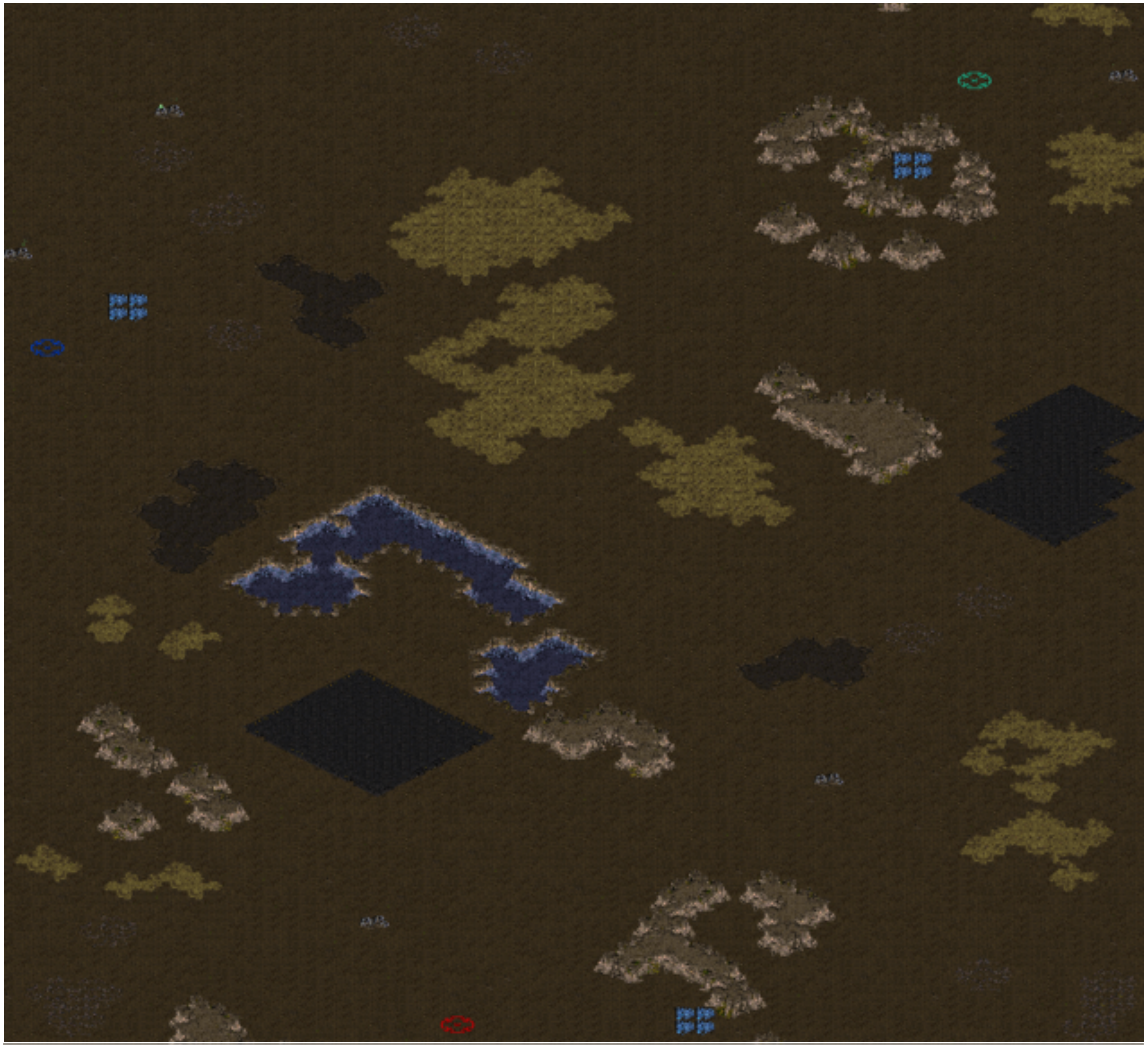
Evolved map

Resource fairness vs. choke points

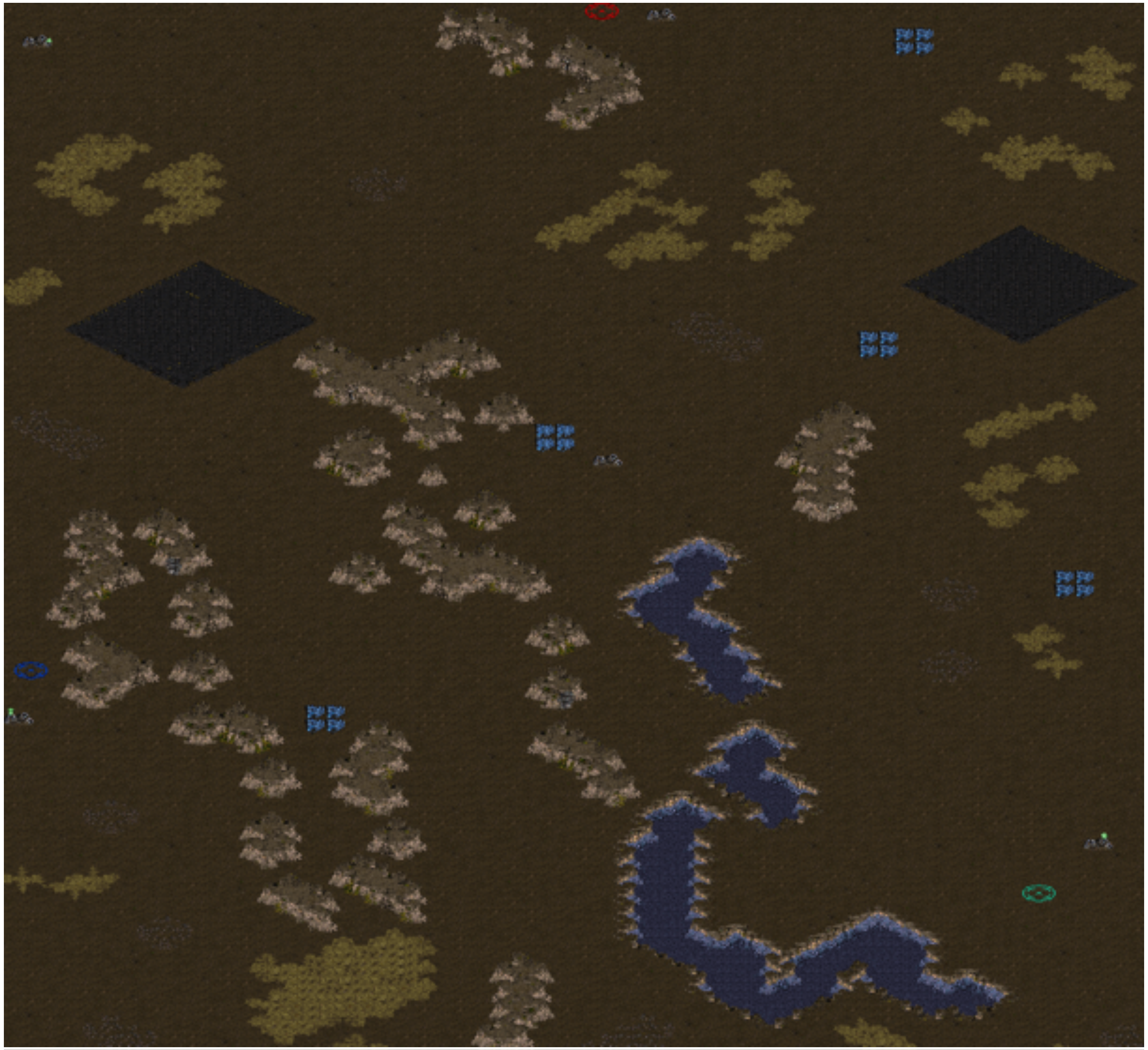


Another evolved map

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.

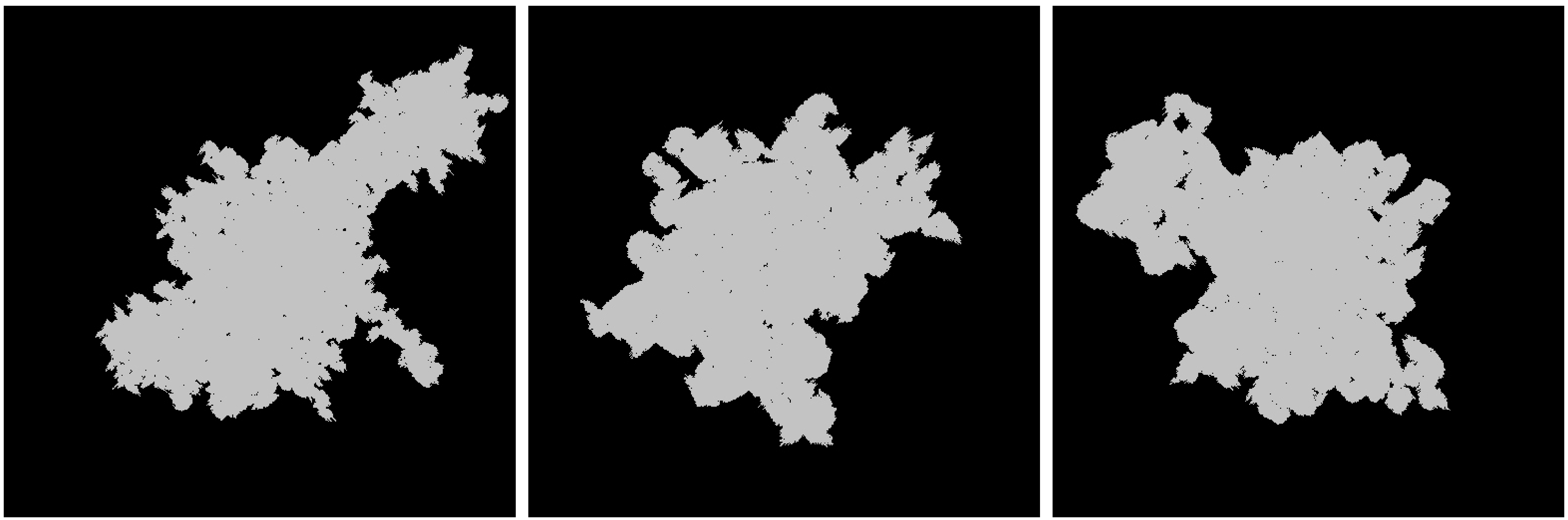
Then came the first coastline agent.

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)
if tokens(agent) ≥ limit
    then
        create 2 child agents
        for each child
            do
                child ← a random seed point on parent's border
                child ← 1/2 of the parent's tokens
                child ← a random direction
                COASTLINE-GENERATE(child)
    else
        for each token
            do
                point ← random border point
                for each point p adjacent to point
                    do
                        score p
                fill in the point with the highest score
```

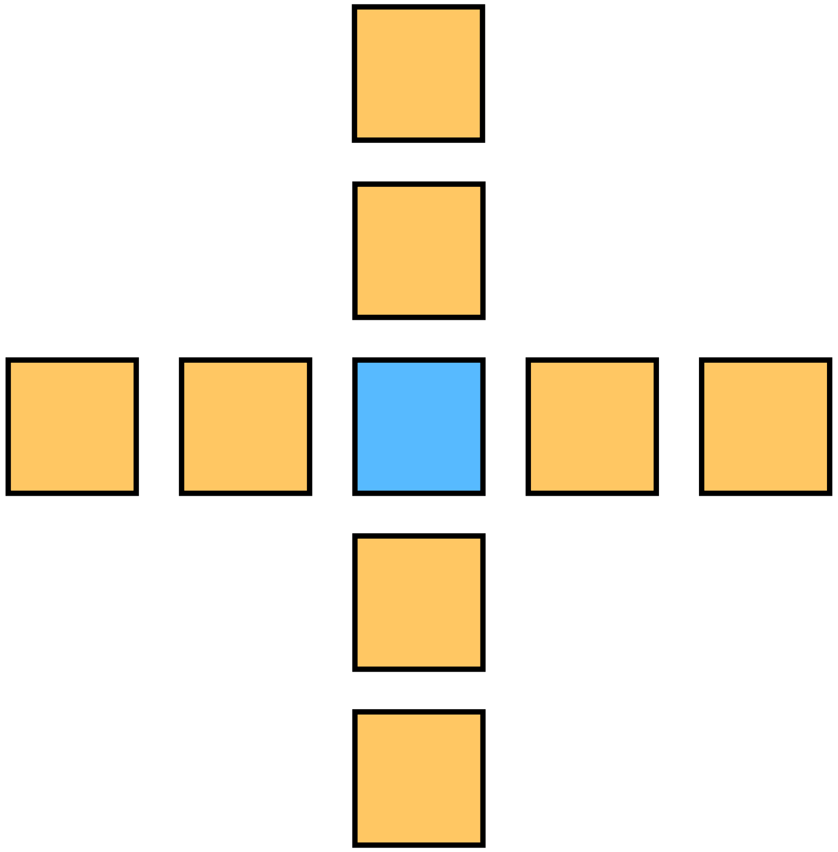
Coastline agents



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*)

location ← *starting-point*
for each *token*
    do
        $height_{location}$ ← weighted average of neighborhood
        location ← random neighboring point

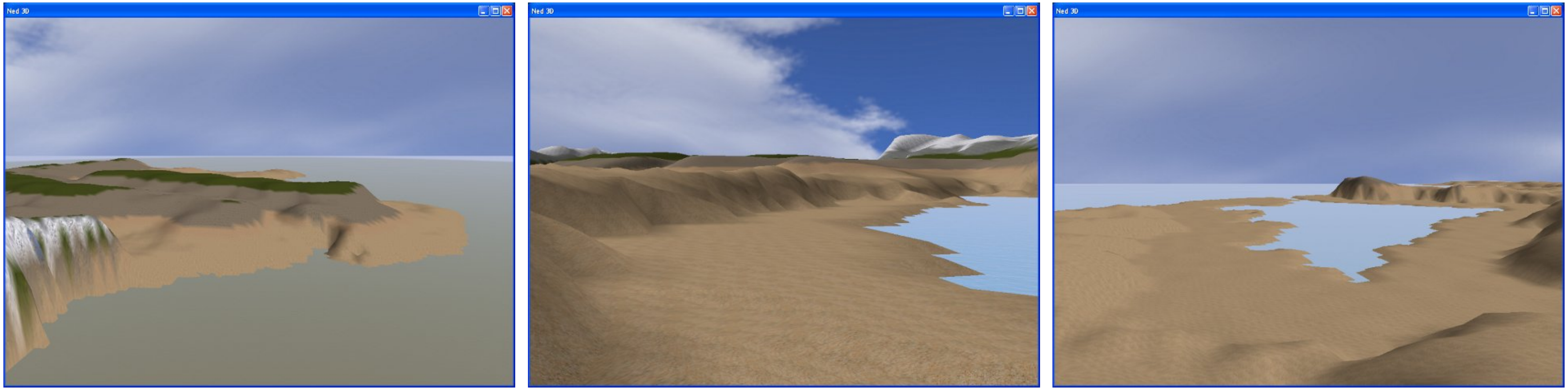
Beach agents

- 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)
location ← starting-point
for each token
        do
            if height_location ≥ limit
               then
                       location ← random shoreline point
            flatten area around location
            smooth area around location
            inland ← random point a short distance inland from location
            for i ← 0 to size(walk)
                   do
                       flatten area around inland
                       smooth area around inland
                       inland ← random neighboring point
            location ← random neighboring point of location
```

Beach agents



Varying beach width

Mountain agents

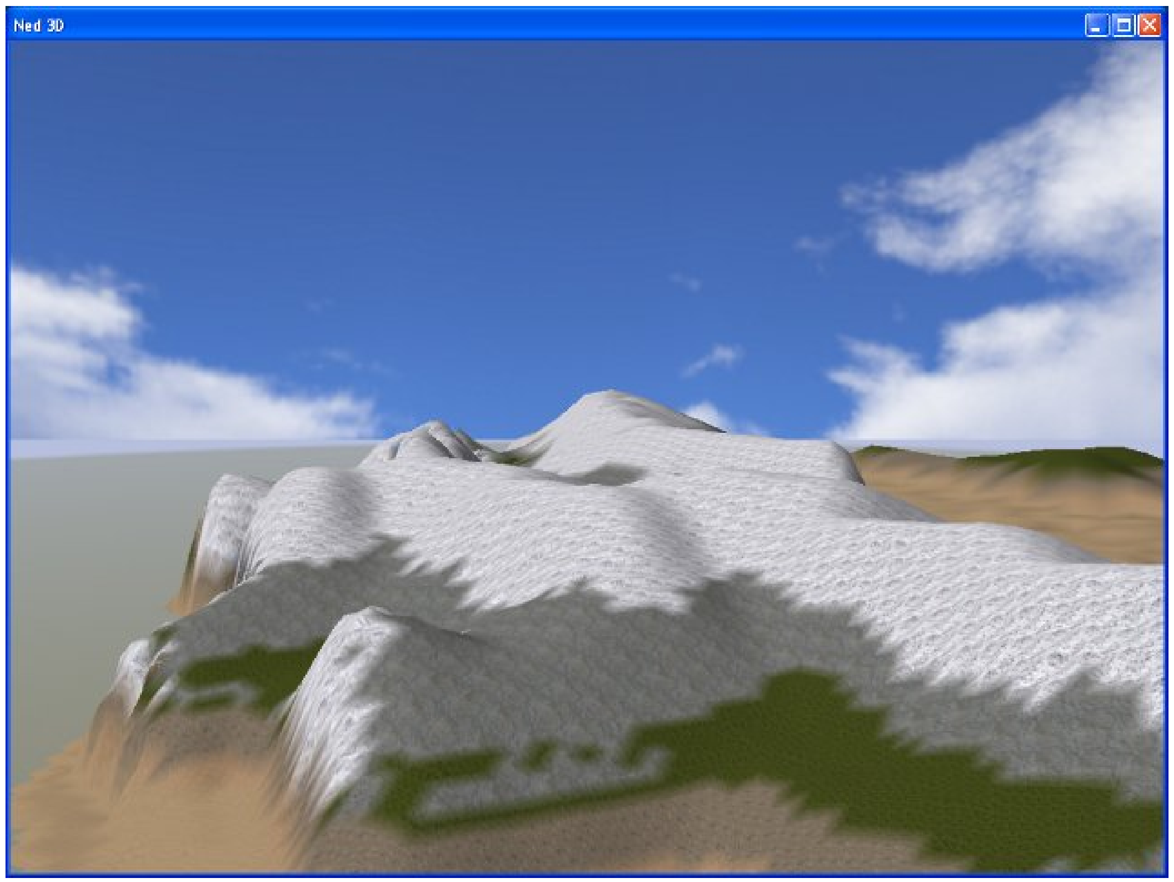
- Start at random positions and directions
- Move forward, continuously elevating a wedge, creating a ridge
- Turn randomly without 45 degrees from the initial course
- Periodically offshoot “foothills” perpendicular to movement direction

Mountain agents

Mountain-Generate(*starting*$_p$*oint*)

```
location ← starting-point
direction ← random direction
for each token
        do
            elevate wedge perpendicular to direction
            smooth area around location
            location ← next point in direction
            every n-th token
                do
                    direction ← original-direction ± 45-degrees
```

Mountain agents



Narrow versus wide features

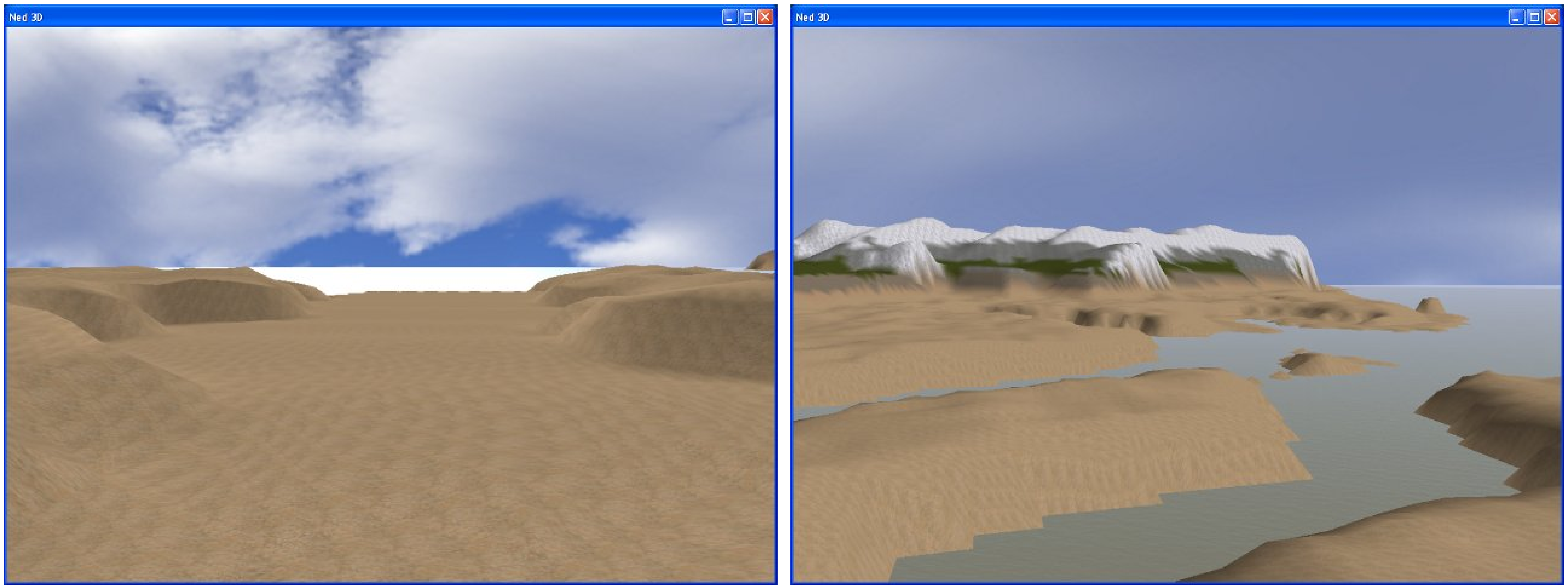
River agents

- 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()
coast ← random point on coastline
mountain ← random point at base of a mountain
point ← coast
while point not at mountain
      do
          add point to path
          point ← next point closer to mountain
while point not at coast
      do
          flatten wedge perpendicular to downhill direction
          smooth area around point
          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?

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"

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.

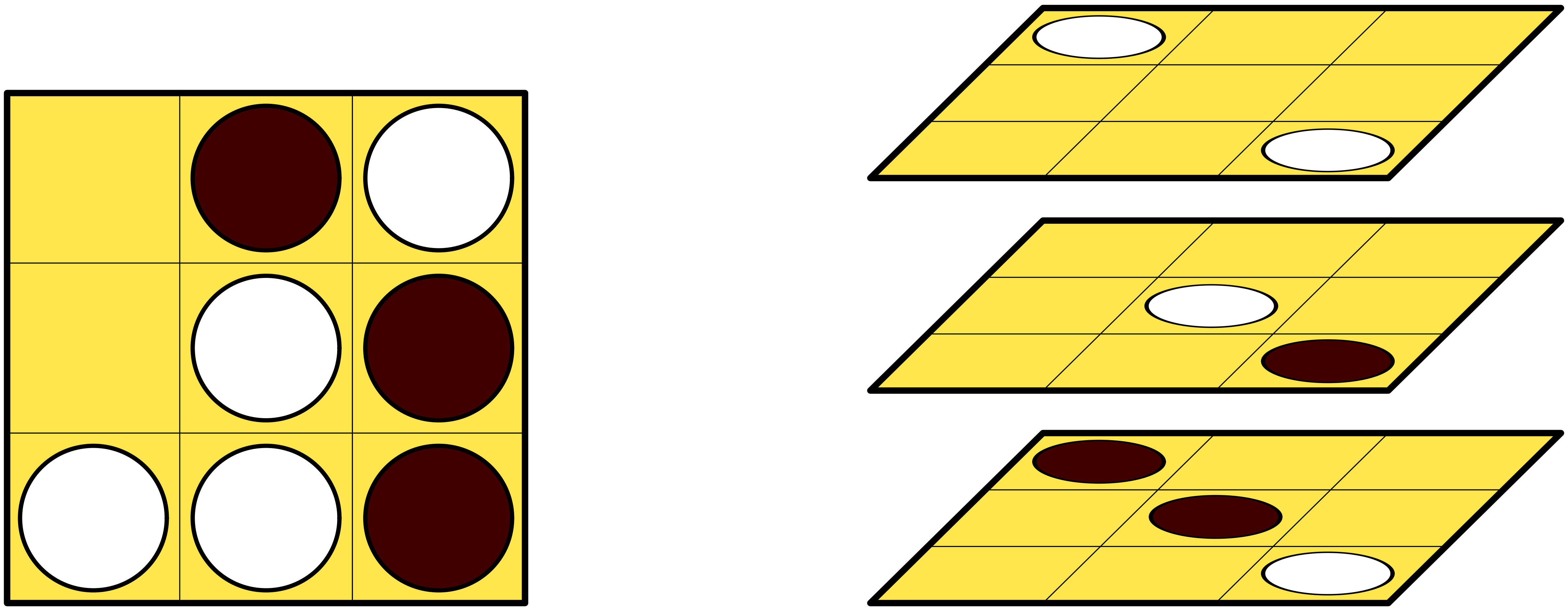
The Ludi Game Description Language

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

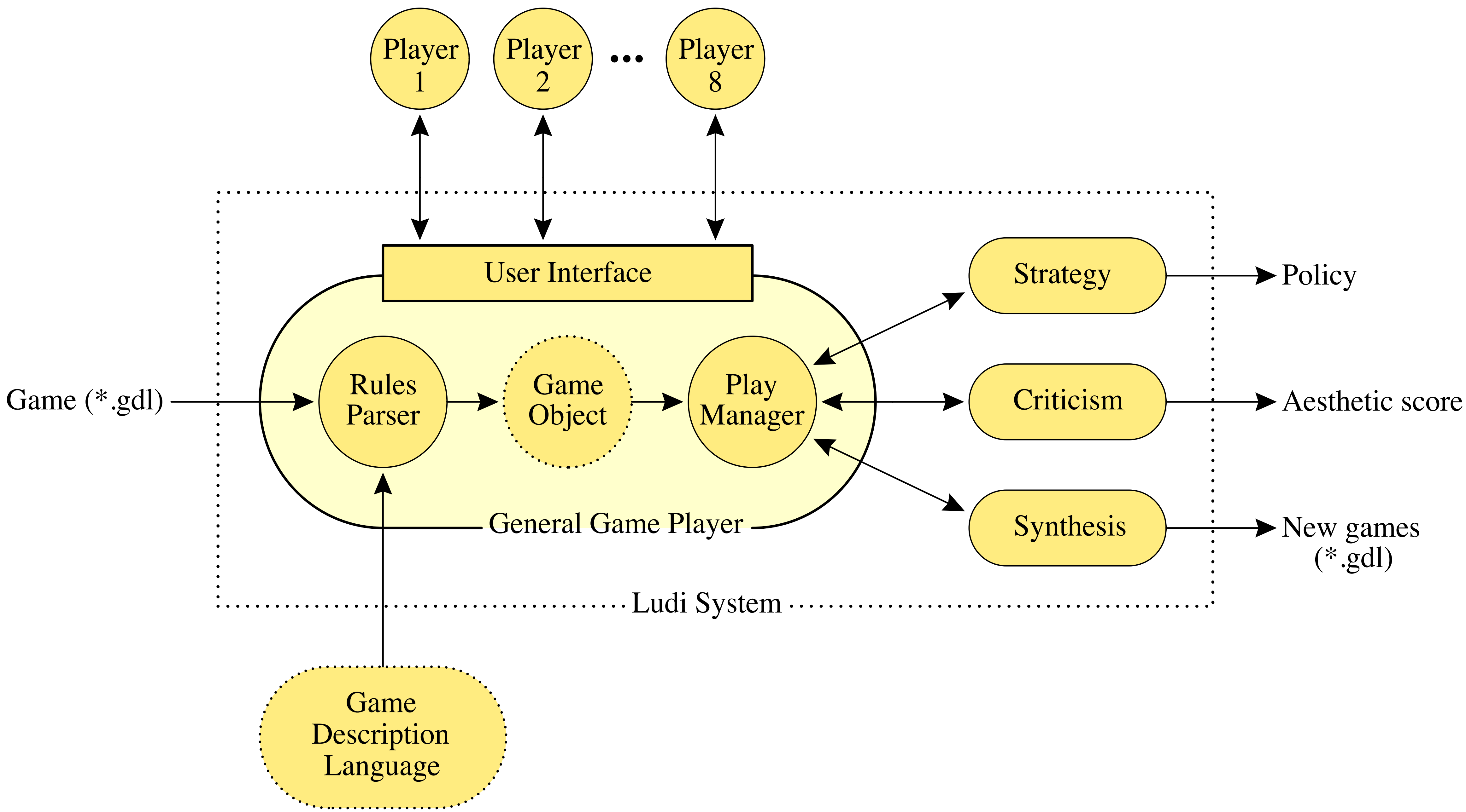
Tic-Tac-Toe

```
(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)



The *Ludi* system

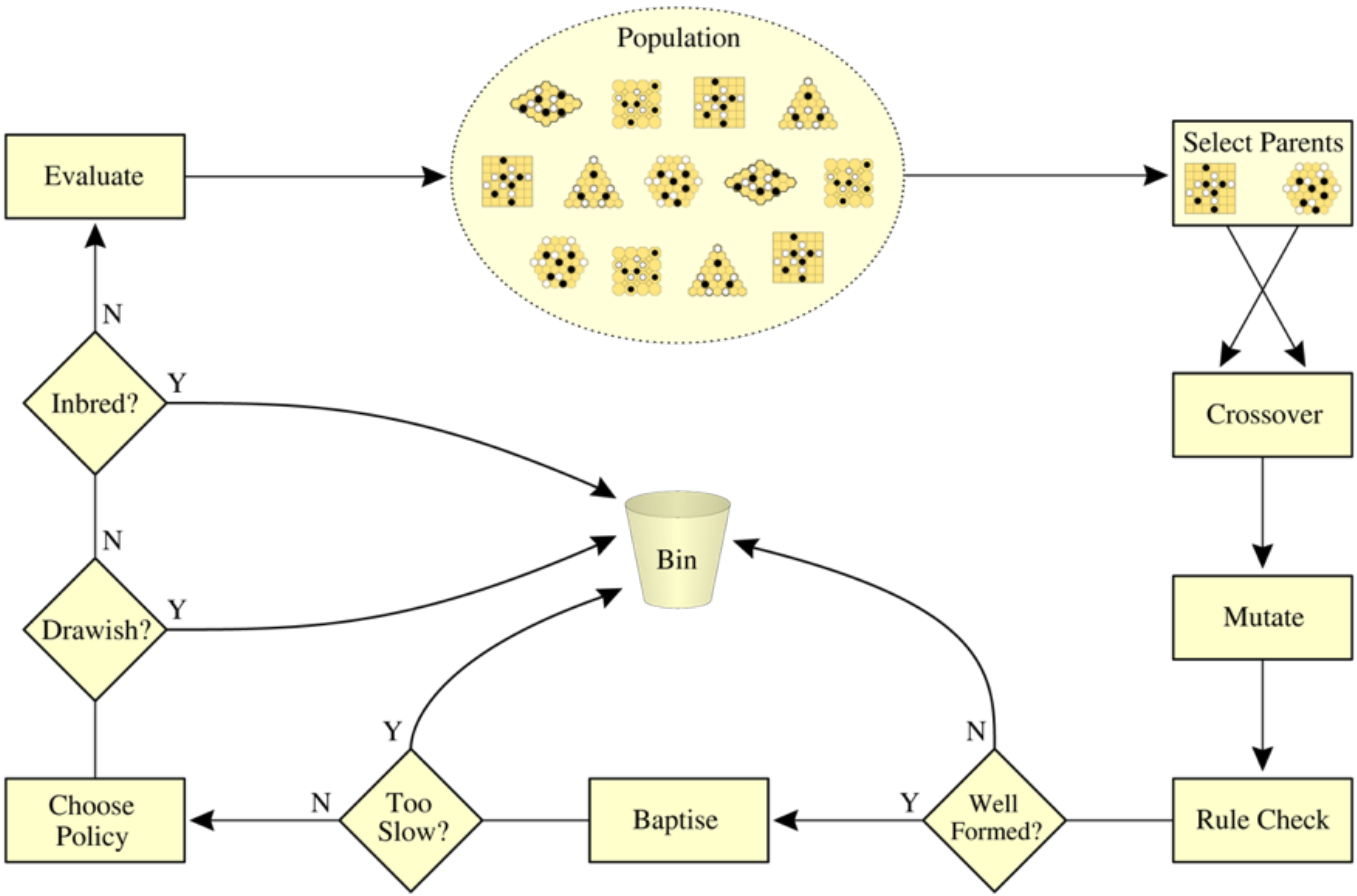


Evaluating a game

- 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

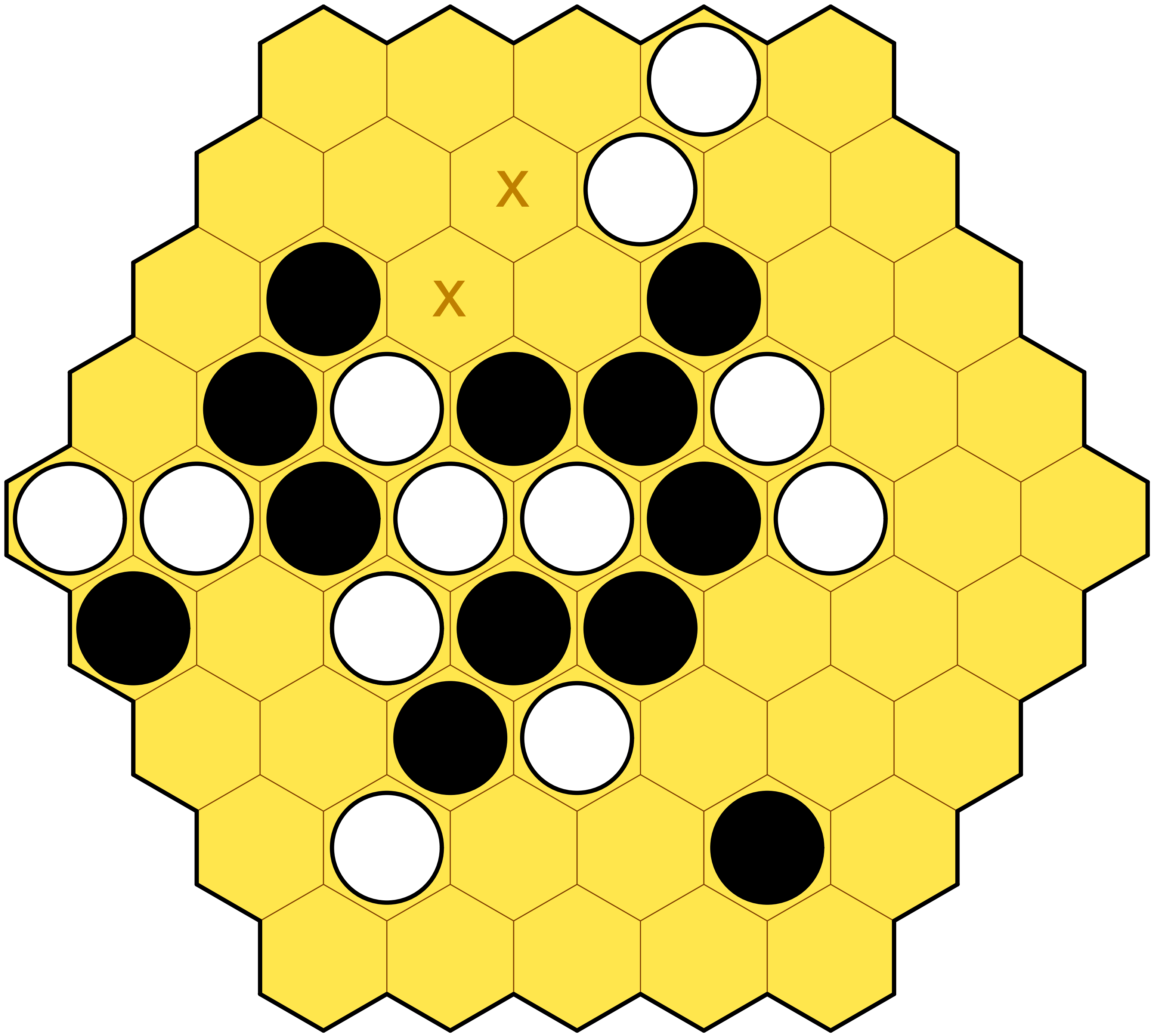
- 16 Intrinsic: based on rules and equipment
- 11 Viability: based on game outcomes
  - e.g. completion, duration
- 30 Quality: based on trends in play
  - e.g. drama, uncertainty


Population
Evaluate
Select Parents
N
Inbred?
Y
Crossover
Bin
N
Drawish?
Y
Mutate
Y
N
Choose
Policy
N
Too
Slow?
Baptise
Y
Well
Formed?
Rule Check

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



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

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

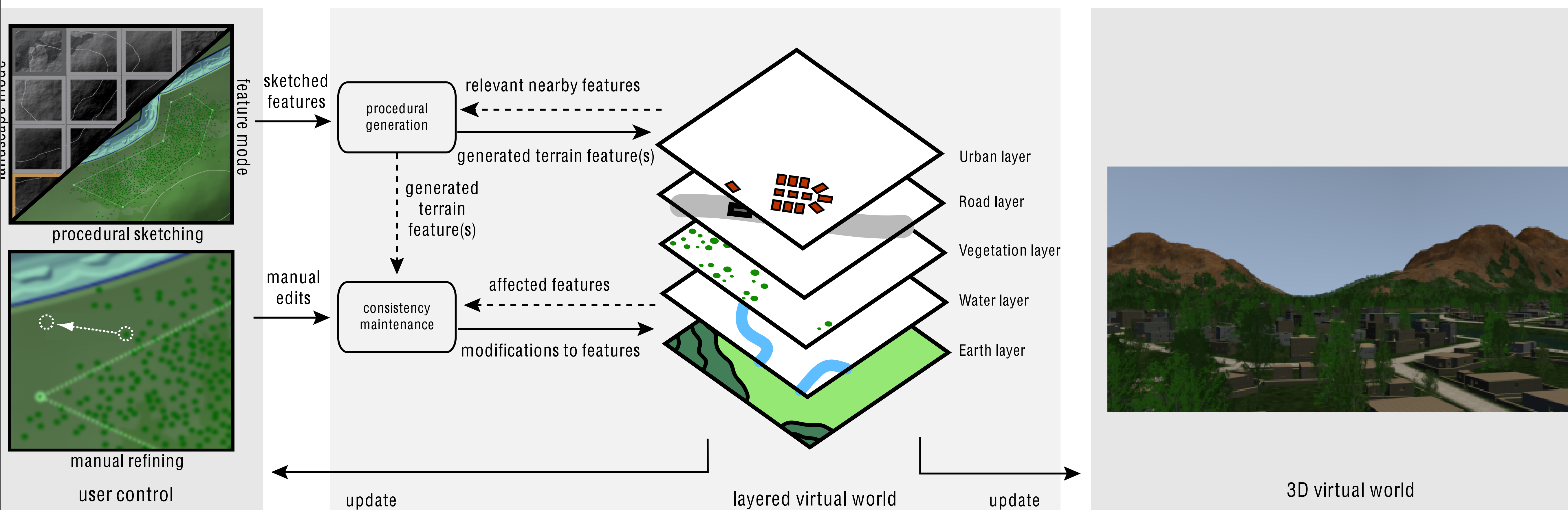
Goals:

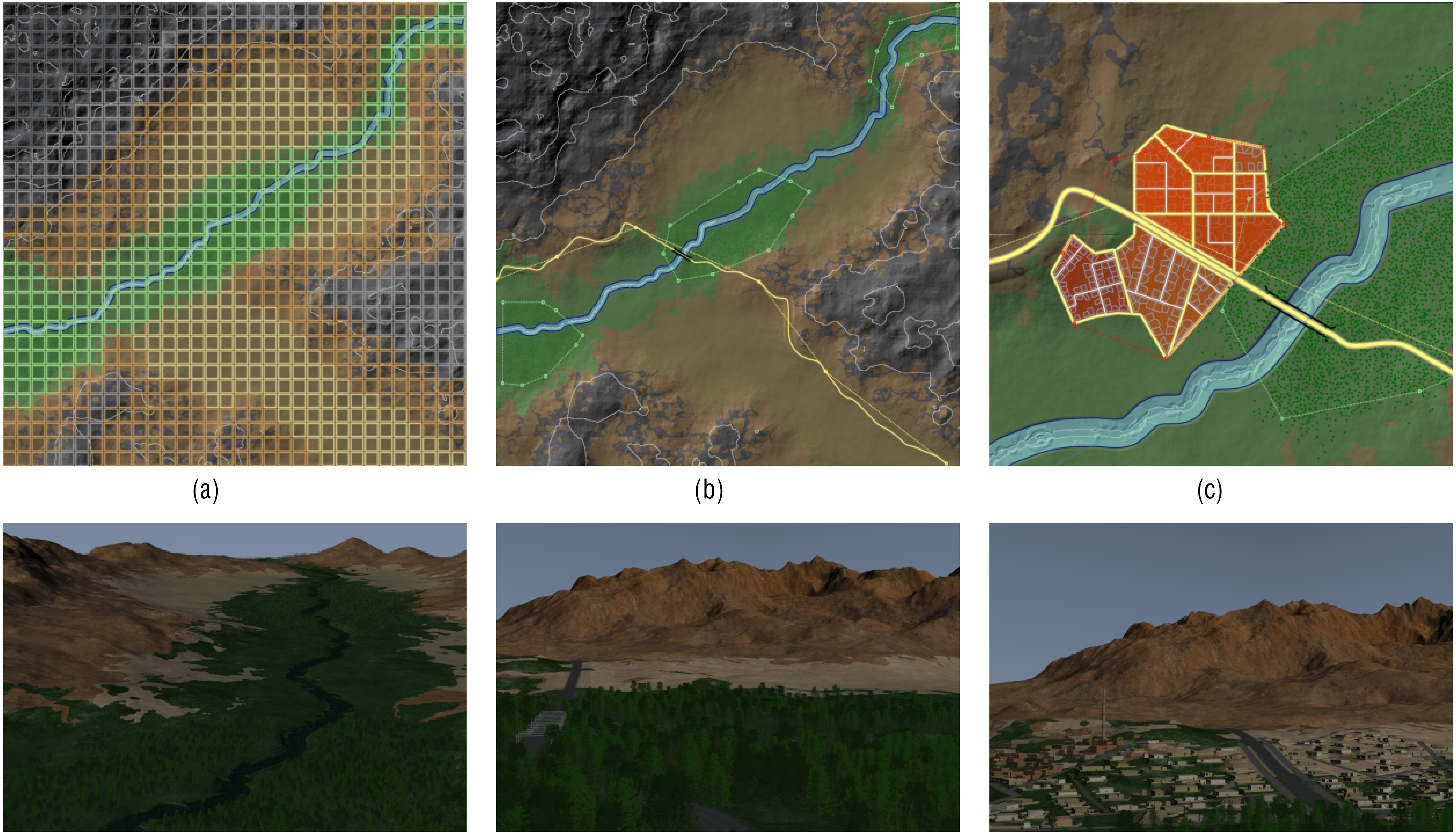
- Increase designers' productivity while retaining creative control
- Provide intuitive way of working with PCG algorithms for non-experts
- Provide framework in which to integrate new PCG research

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





(a) (b) (c) (d) (e) (f)

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 ?

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