



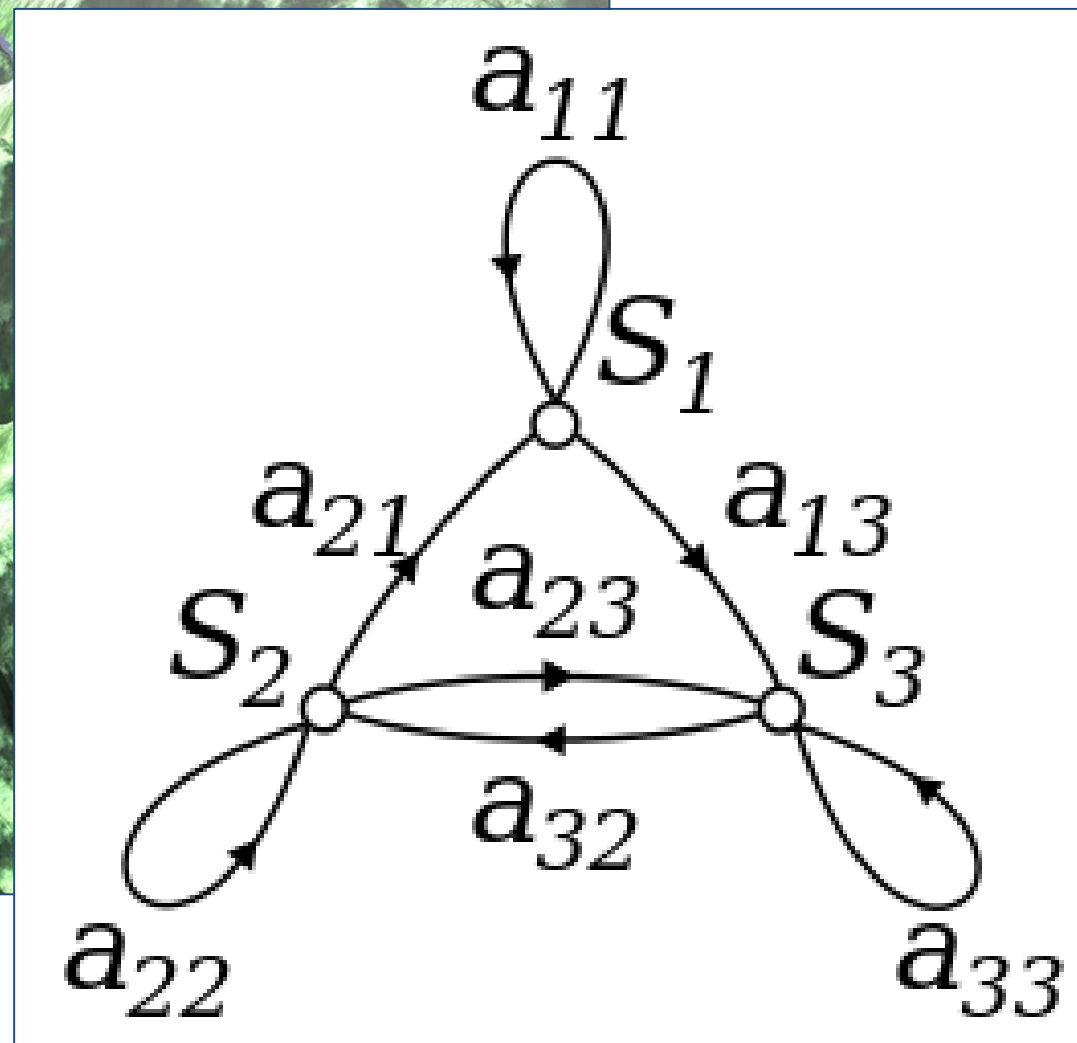
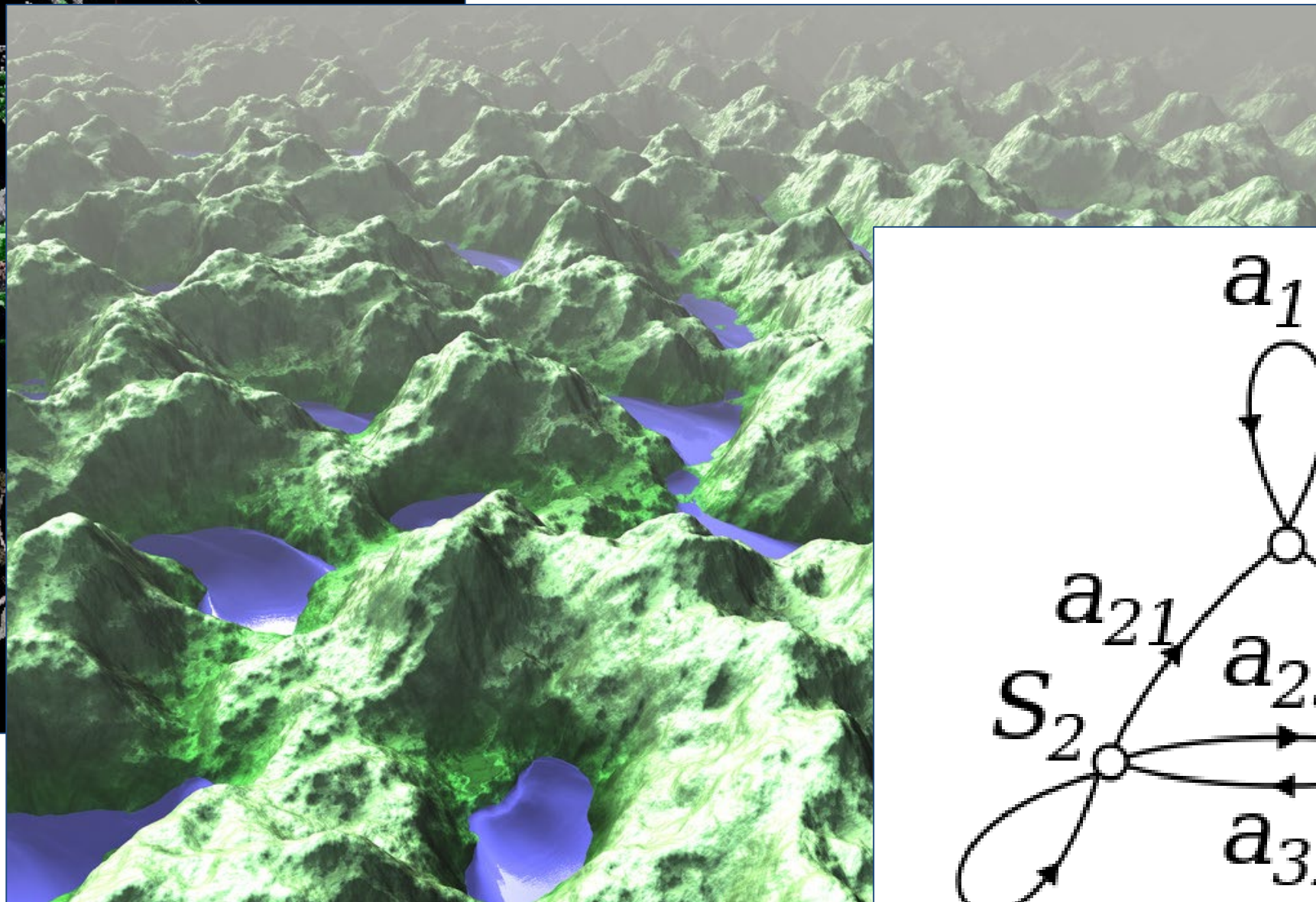
Math for Game Developers: End-to-End Procedural Generation in *Caves of Qud*

Jason Grinblat & Brian Bucklew
Co-founders at Freehold Games

GAME DEVELOPERS CONFERENCE

MARCH 18–22, 2019 | #GDC19

- 1: Nevit Dilmen, [L-system-Airhorse](https://creativecommons.org/licenses/by-sa/3.0), <https://creativecommons.org/licenses/by-sa/3.0>
2: User:Syntopia, [Noise-based Terrain Generation](https://creativecommons.org/licenses/by/2.0), <https://creativecommons.org/licenses/by/2.0>
3: User:Chrislb, [Simple markov chain](https://creativecommons.org/licenses/by-sa/3.0), <https://creativecommons.org/licenses/by-sa/3.0>



Why are we here?

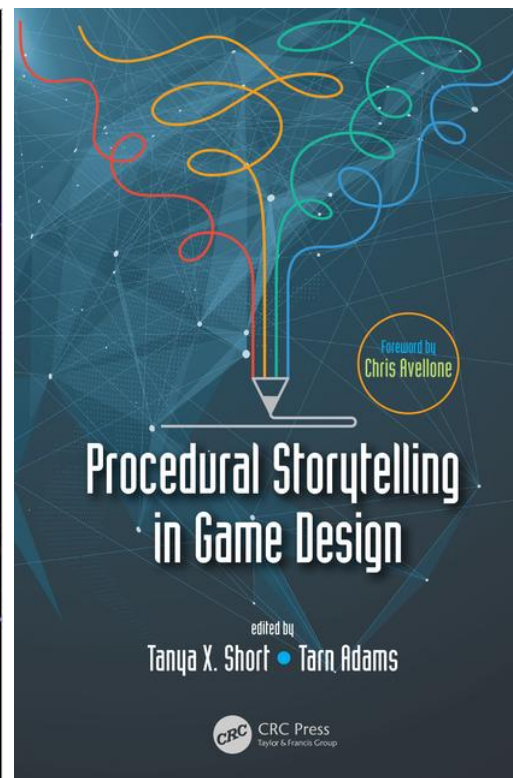
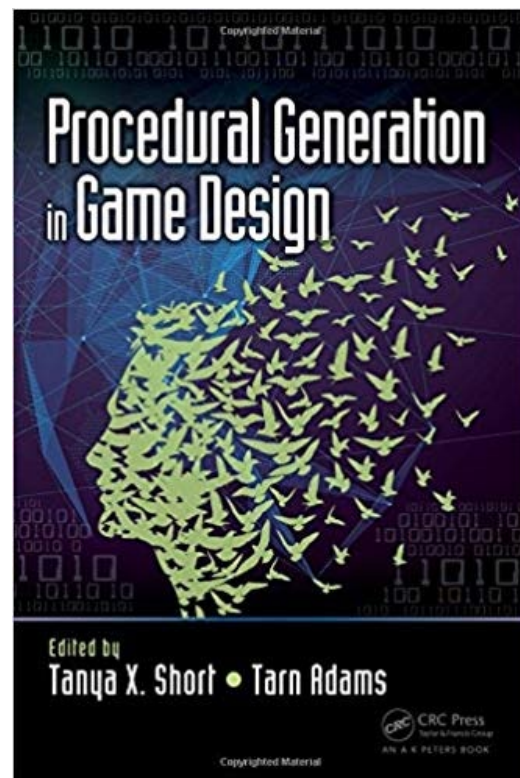
PROBLEM STATEMENT: How do you combine procgen techniques to build large-scale generative systems?



JASON GRINBLAT
@ptychomancer



BRIAN BUCKLEW
@unormal



Caves of Qud

- Open-world, science fantasy RPG and roguelike
- *“Chisel through a layer cake of thousand-year-old civilizations.”*
- Handcrafted narrative + simulative systems
- Extensive use of procgen



Why are we here?

PROBLEM STATEMENT: How do you combine procgen techniques to build large-scale generative systems?

CASE STUDY: Procedurally generated villages in *Caves of Qud*

Agenda

- Design context
- Broad approach
- What makes a village?
- Techniques we use
- ★ Village generation ★
- Takeaways

Design Context

- We're making an RPG, so we take a simulative approach to design
- Perspective is limited to a player avatar
- We value novelty in output, so we let our generators run wild



SimCity 4 (Maxis, 2003)

User:haljackey, [SimCity 4 Downtown Traffic](https://creativecommons.org/licenses/by-sa/2.0/), <https://creativecommons.org/licenses/by-sa/2.0/>

Design Context

- We're making an RPG, so we take a simulative approach to design
- Perspective is limited to a player avatar
- We value novelty in output, so we let our generators run wild

Design Context

Modularity is good!

- Software design perspective: decoupled modules are tractable
- Game design perspective: decoupled modules compose into varied and novel output



Abstract Peak



Concrete Valley

Broad Approach

- Generate a village over multiple steps
 - Model village facets at various levels of abstraction
 - Use abstract models as input to later steps
 - Reify! (abstract → concrete)
 - If no abstract input is available, use defaults
- It's all about the plumbing: INPUT & OUTPUT



What Makes a Village?

- Villagers (NPCs)
- History
- Geography
- Architecture
- Government
- Cultural practices
- Religion
- Storytelling tradition
- Relationship with local resources
- Furniture
- Food & drink
- Proverbs
- Collective & personal needs (Quests)

Techniques We Use

- Population tables
- Noise maps
- Wave function collapse
- State machines
- Replacement grammars
- Dijkstra mapping
- Dynamic image manipulation
- Pathfinding
- ECA with hand-defined prefabs
- Inversion of control

Village Generation

Design

Define prefabs

- Object blueprints
- Population tables
- Static factions
- Historic event templates
- Quest templates

World Gen

Generate history

- Name
- Base faction
- Region
- Government (ex)
- Religion (ex)
- Signature ingredients (ex)

Resolve neighbors

- Location
- Relationship with local sites and NPCs

Fabrication

Generate culture

- Cultural practices
- Storytelling tradition
- Signature dish

Generate architecture

- Style
- Map of buildings

Fabricate game objects

- NPCs with dialog
- Furniture

Abstract Peak

Generate history

Resolve neighbor relationships

Generate culture

Generate architecture

Fabricate game objects

Concrete Valley



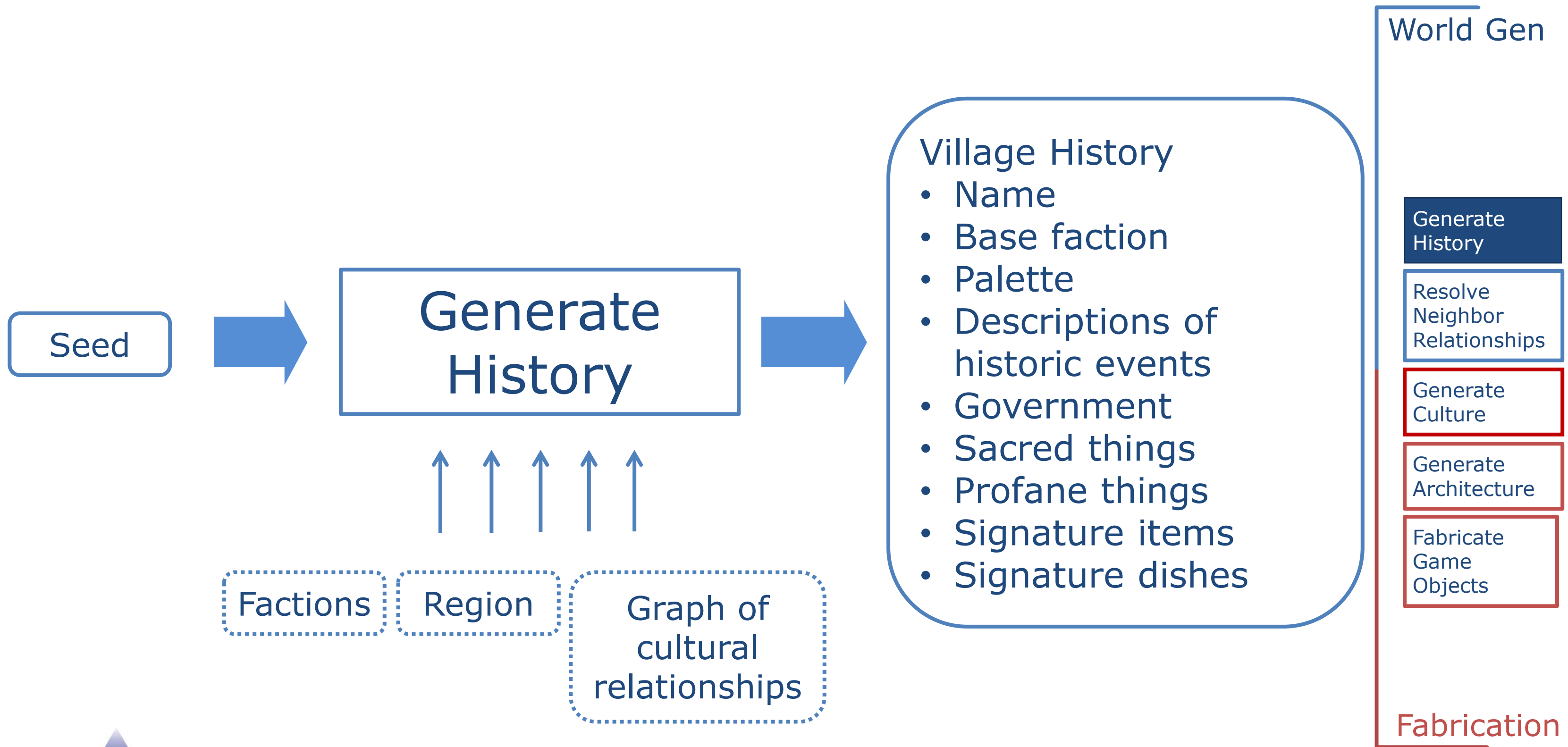
carved diptych

A narrative is confined to the etched boundaries of this stone, to the reductive duality of its form.

This object is a monument to a scene from the history of the village **Nawan**:

In 790, the villagers of Nawan demanded that the mayor abdicate and all forms of hierarchy be abolished from their village. The two pillars of civic life in Nawan thus became anarchy and Valator, legendary giant dragonfly.

Perfect



Village Generation

Design

Define prefabs

- Object blueprints
- Population tables
- Static factions
- Historic event templates
- Quest templates

World Gen

Generate history

- Name
- Base faction
- Region
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Resolve neighbors

- Location
- Relationship with local sites and NPCs

Fabrication

Generate culture

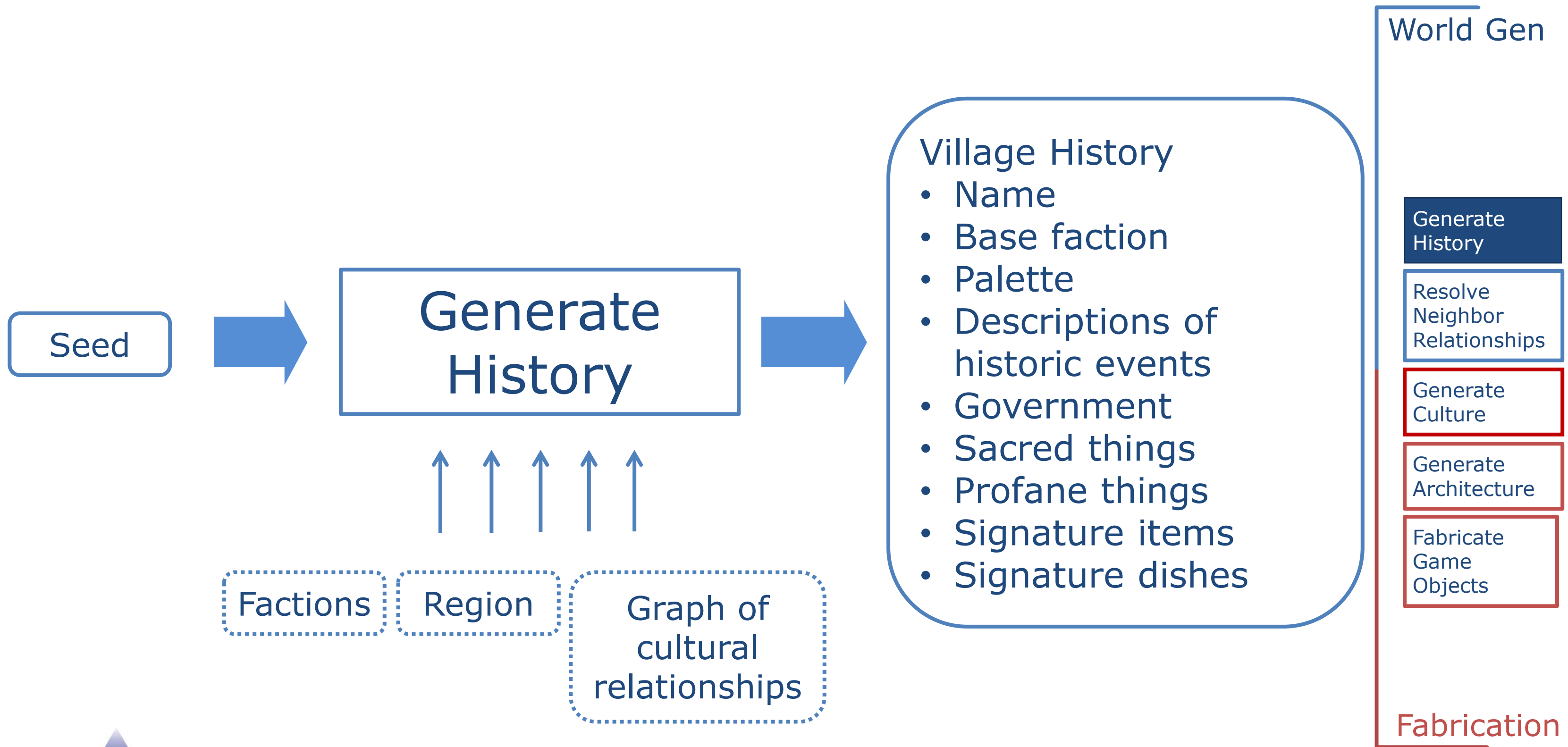
- Cultural practices
- Storytelling tradition
- Signature dish

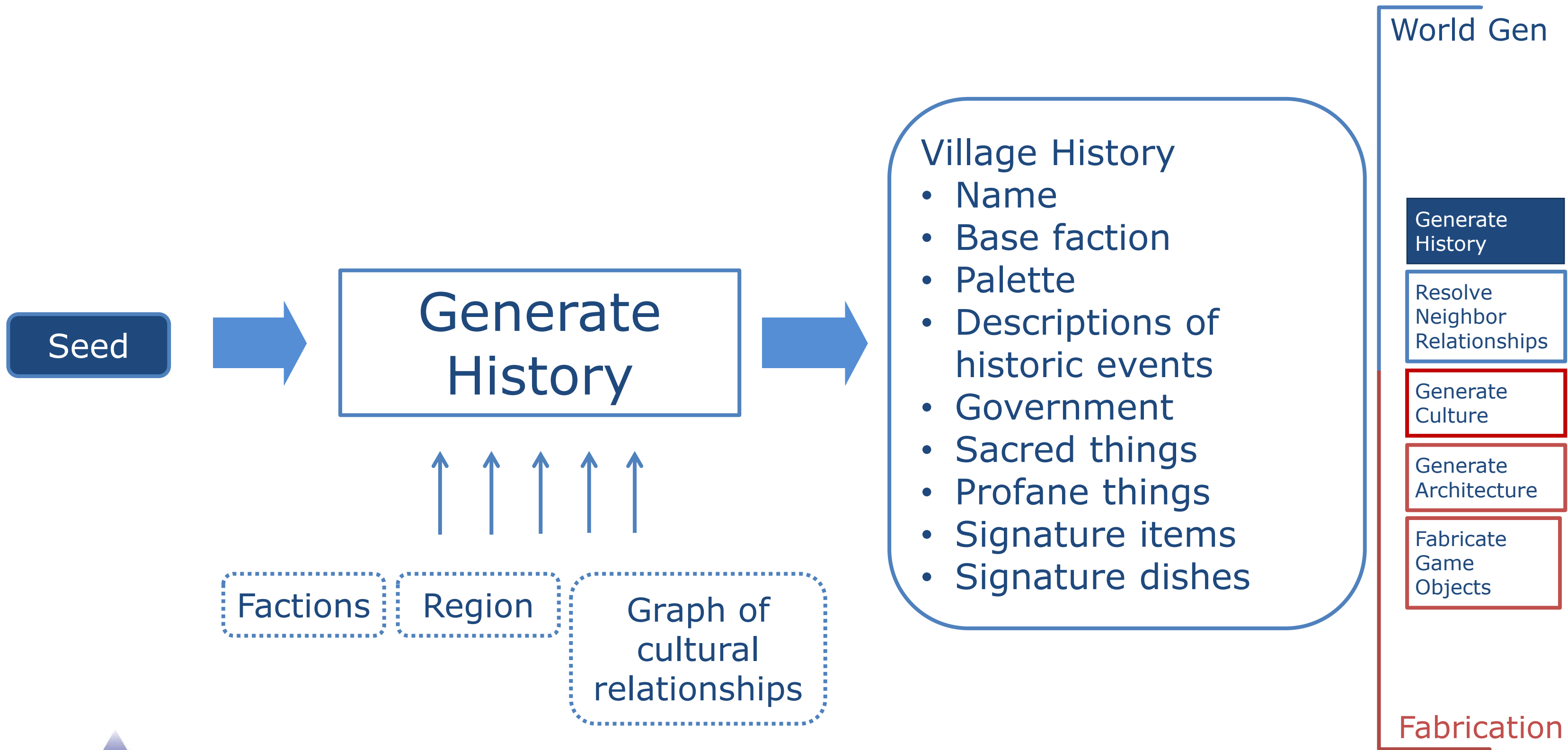
Generate architecture

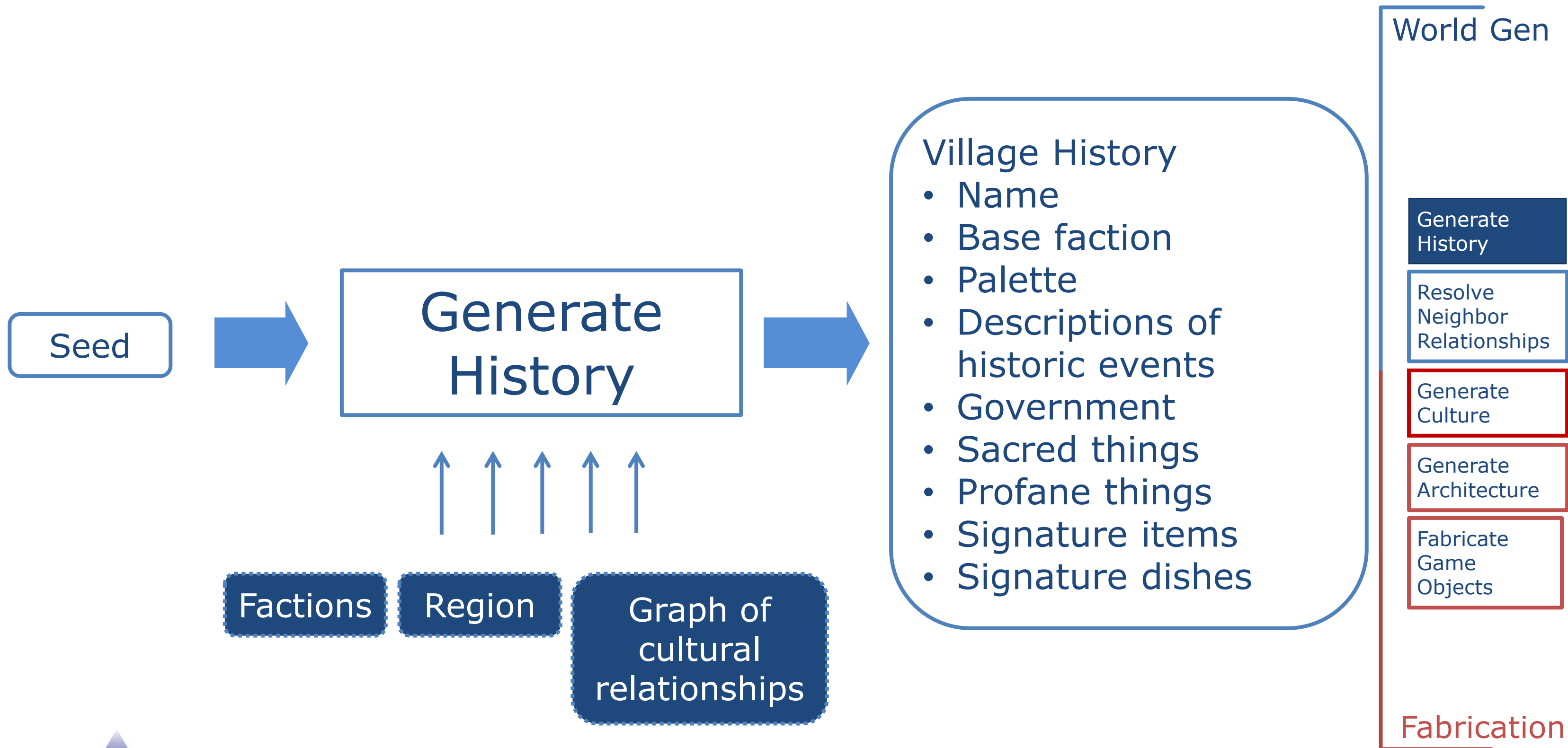
- Style
- Map of buildings

Fabricate game objects

- NPCs with dialog
- Furniture







Factions

World Gen

[Reputation] ESC or 5 to exit

Faction	Reputation	
antelopes	0	Antelopes don't care about you, but aggressive ones will attack you.
apes	0	
arachnids	-475	
baboons	-300	
baetyls	0	You aren't welcome in their holy places.
Barathrumites	0	
bears	-475	
birds	0	Antelopes are interested in trading secrets about the locations of water weeps, the locations of cat lairs, and sultans they admire or despise. They're also interested in hearing gossip that's about them.
cannibals	-500	
cats	-300	
Children of Mamon	-600	
Consortium of Phyta	-10	
crabs	-475	
cragmensch	-500	
dogs	300	
dressed merchants	0	

Generate History

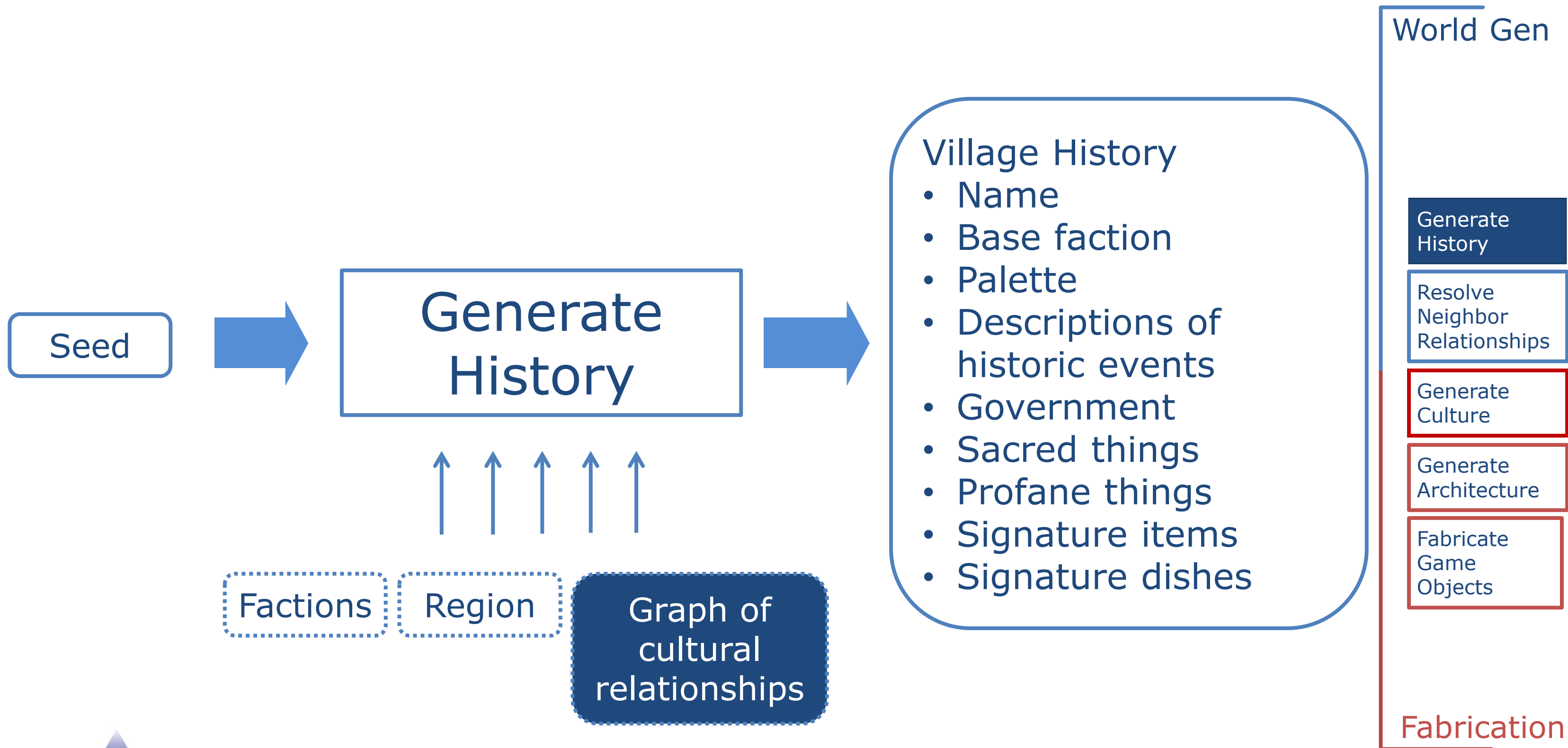
Resolve Neighbor Relationships

Generate Culture

Generate Architecture

Fabricate Game Objects

Fabrication



Graph of cultural relationships

World Gen

```
"villages" :
{
  "description" : ["*terrainFragment* <spice.commonPhrases.people.!random> <spice.commonPhrases.gather.!random> in <spice.commonPhrases.reverence.!random> of *sacredThing*",
    "<spice.commonPhrases.people.!random> <spice.commonPhrases.gather.!random> *terrainFragment* in <spice.commonPhrases.reverence.!random> of *sacredThing*",
    "*terrainFragment* <spice.commonPhrases.people.!random> <spice.commonPhrases.gather.!random> to <spice.commonPhrases.profane.!random> *profaneThing*",
    "<spice.commonPhrases.people.!random> <spice.commonPhrases.gather.!random> *terrainFragment* to <spice.commonPhrases.profane.!random> *profaneThing*",
    "*terrainFragment* there's a <spice.commonPhrases.gathering.!random> of *faction* and their <spice.commonPhrases.kin.!random>",
    "there's a <spice.commonPhrases.gathering.!random> of *faction* and their <spice.commonPhrases.kin.!random> *terrainFragment*"],
  "reasonForFounding" :
  {
    "farming" :
    {
      "defaultFoundingText" : ["because of the *ArableLand* nearby"],
      "sacredThing" : ["finding *ArableLand* for those who love *SacredThing*"],
      "profaneThing" : ["those who oppose *ArableLand* and *SacredThing*"]
    },
    "escapePersecution" :
    {
      "defaultFoundingText" : ["to escape persecution from those who despise *SacredThing*"],
      "sacredThing" : ["escaping persecution for loving *SacredThing*"],
      "profaneThing" : ["the persecutors of those who love *SacredThing*"]
    },
    "monastery" :
    {
      "defaultFoundingText" : ["for the contemplation of *SacredThing*"],
      "sacredThing" : ["the contemplation of *SacredThing*"],
      "profaneThing" : ["profaning *SacredThing*"]
    },
    "outpost" :
    {
      "defaultFoundingText" : ["to defend *SacredThing* and the practice of *Activity*"],
      "sacredThing" : ["defending *SacredThing*"],
      "profaneThing" : ["attacking *SacredThing*"]
    }
  }
}
```

Generate
History

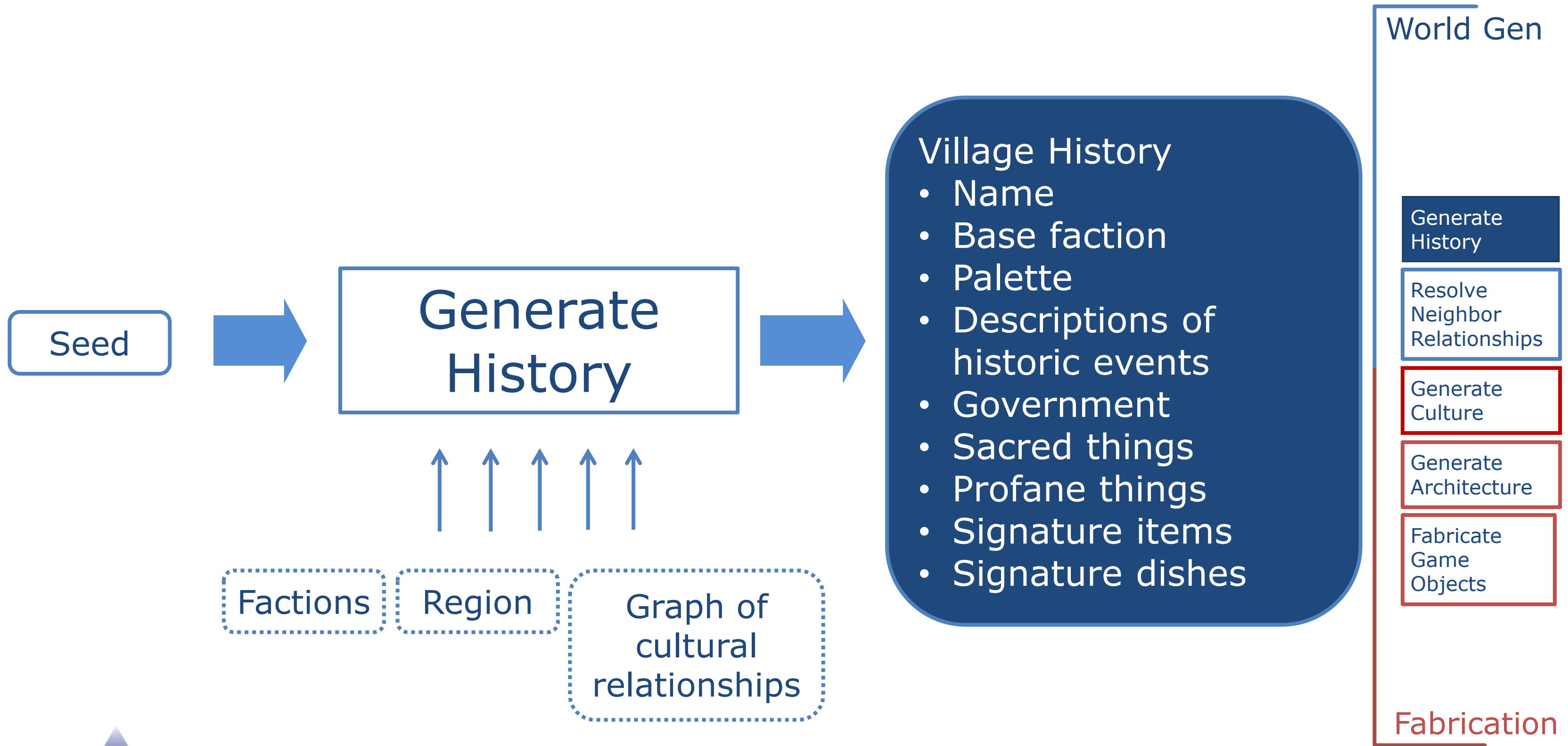
Resolve
Neighbor
Relationships

Generate
Culture

Generate
Architecture

Fabricate
Game
Objects

Fabrication



Village history

World Gen

Generate
History

Resolve
Neighbor
Relationships

Generate
Culture

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Architecture

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Game
Objects

Fabrication

▲ villageSnapshot	"---snapshot-----\r\n\r\n--properties---\r\n\r\n type = village name = Iravuh region = DesertCanyon
🔧 Name	"Iravuh"
🔧 TechTier	2
🔧 Tier	1
🔧 _TechTier	2
🔧 _Tier	1
▶ 📦 entity	{HistoryKit.HistoricEntity}
▶ 📦 listProperties	Count=10
🔧 profaneThing	"those who would harm Somsatashi, legendary feral dog"
▲ 📦 properties	Count=14
▶ 📦 ["type"]	"village"
▶ 📦 ["name"]	"Iravuh"
▶ 📦 ["region"]	"DesertCanyon"
▶ 📦 ["tier"]	"1"
▶ 📦 ["techTier"]	"2"
▶ 📦 ["villagerPopulation"]	"nonHumanoid"
▶ 📦 ["baseFaction"]	"Equines"
▶ 📦 ["reasonForFounding"]	"monastery"
▶ 📦 ["defaultSacredThing"]	"the contemplation of abundant food"
▶ 📦 ["defaultProfaneThing"]	"profaning the act of procreating"
▶ 📦 ["governor"]	"the mayor"
▶ 📦 ["signatureDishName"]	"Abundant's Slaw"
▶ 📦 ["proverb"]	"Live and drink."
▶ 📦 ["zoneID"]	"JoppaWorld.18.9.1.1.10"
▶ 📦 Raw View	Count=14
🔧 sacredThing	"Somsatashi, legendary feral dog"
📦 villagerBaseFaction	"Joppa"

Village history



World Gen

Generate History

Resolve Neighbor Relationships

Generate Culture

Generate Architecture

Fabricate Game Objects

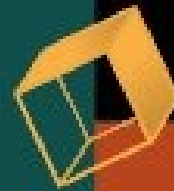
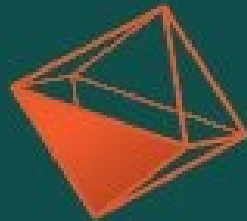
Fabrication

GDC

GAME DEVELOPERS CONFERENCE

MOSCONE CENTER
SAN FRANCISCO, CA

MARCH 19-23, 2018
EXPO: MAR 21-23, 2018

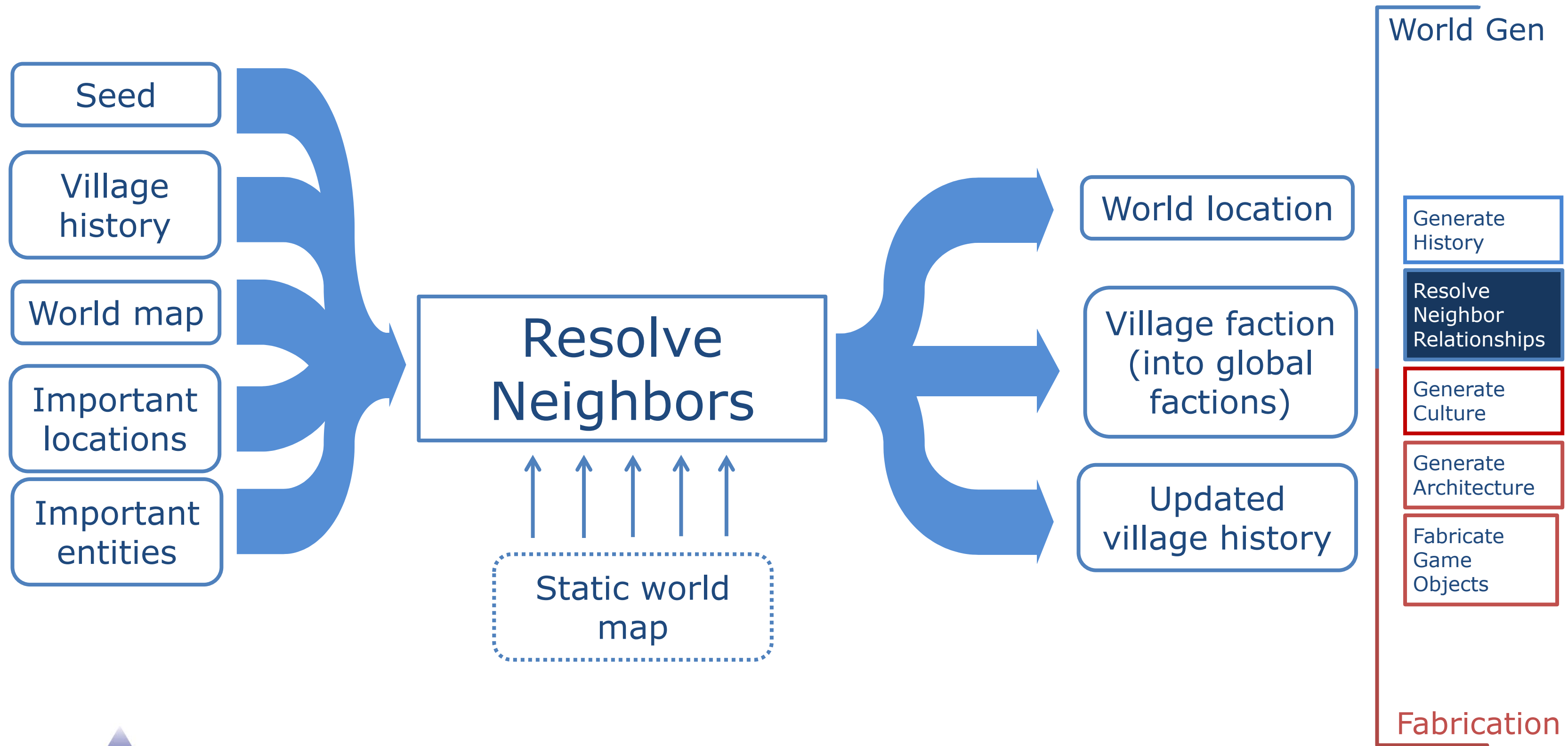


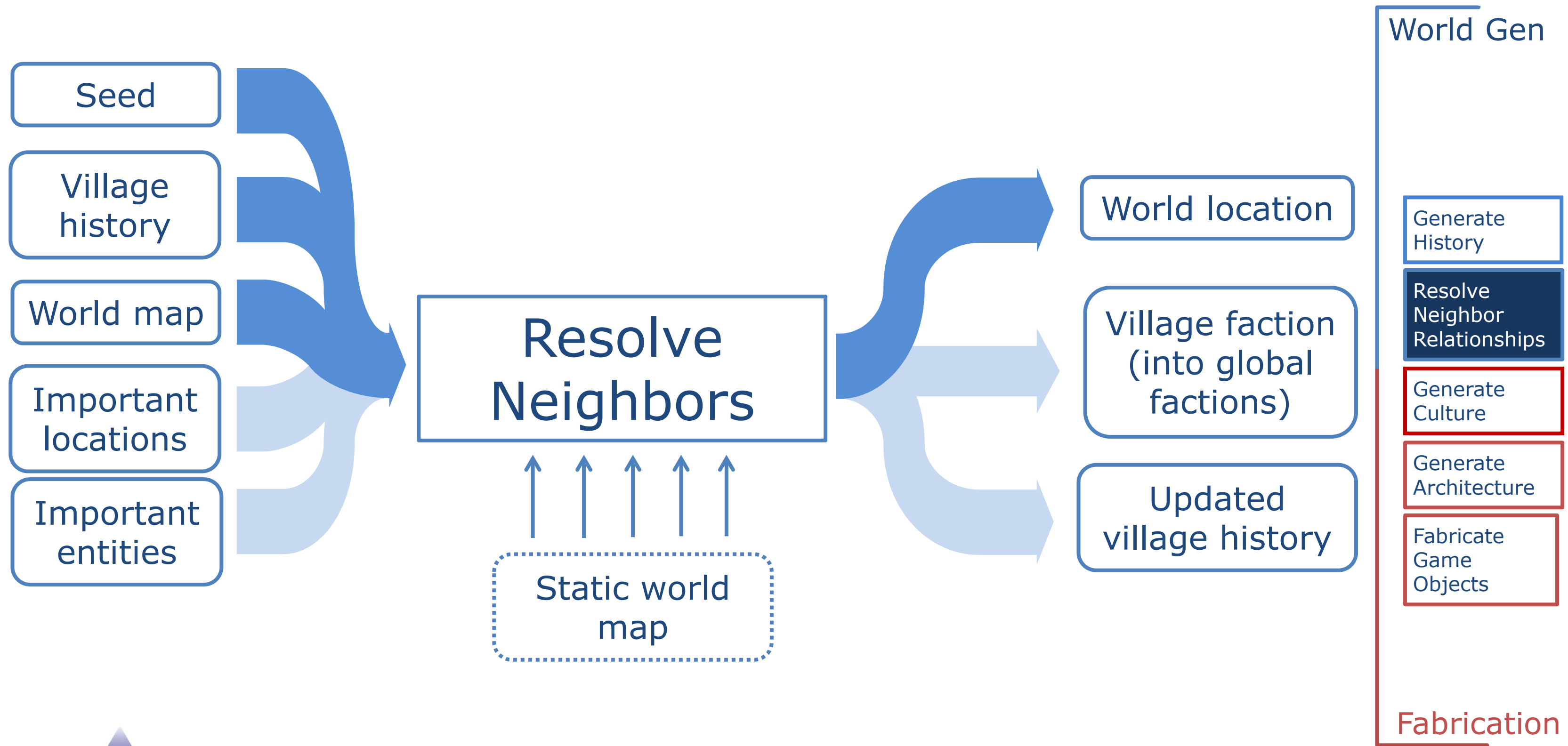
*Jason Grinblat
(Freehold Games)*

Procedurally Generating History in 'Caves of Qud'

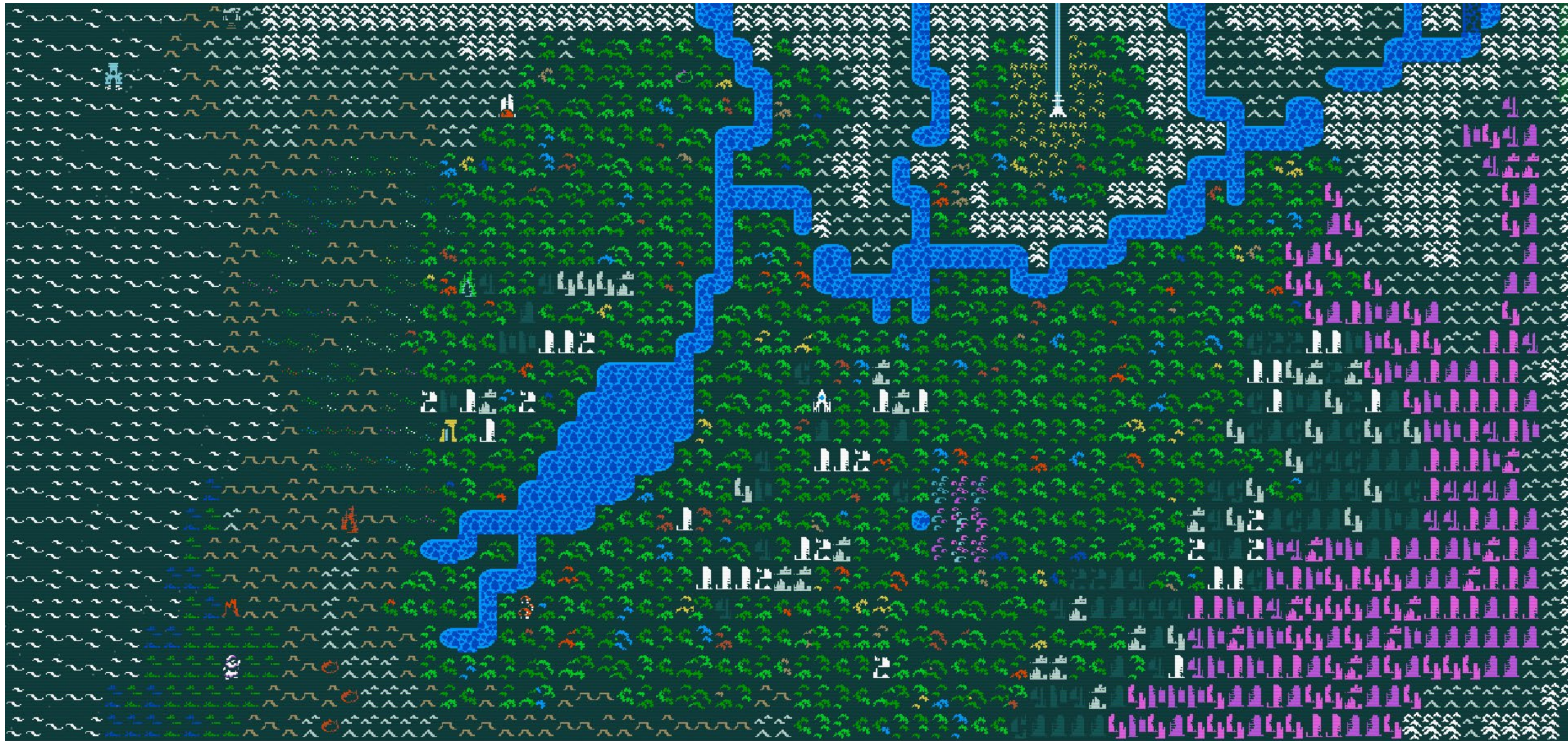


@Official_GDC





Static world map



World Gen

Generate History

Resolve Neighbor Relationships

Generate Culture

Generate Architecture

Fabricate Game Objects

Fabrication

Static world map

```
<cell Name="Jungle" Inherits="DefaultJoppaCell" ApplyTo="TerrainJungle">
  <zone Level="10" x="0-2" y="0-2" Name="Jungle">
    <encounter Table="Jungle" Amount="low"></encounter>
    <builder Class="FactionEncounters" Population="GenericFactionPopulation"></builder>
    <builder Class="Music" Track="Overworld1" Chance="10"></builder>
  </zone>
  <zone Level="11-15" x="0-2" y="0-2" Name="Subterranean Jungle">
    <builder Class="Strata"></builder>
    <builder Class="ZoneTemplate:JungleCaves"></builder>
    <builder Class="PossibleCryotube"></builder>
    <builder Class="FactionEncounters" Population="GenericFactionPopulation"></builder>
    <builder Class="Music" Track="Overworld1" Chance="10"></builder>
  </zone>
</cell>
```

World Gen

Generate History

Resolve Neighbor Relationships

Generate Culture

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Fabricate Game Objects

Fabrication

World Gen



Generate History

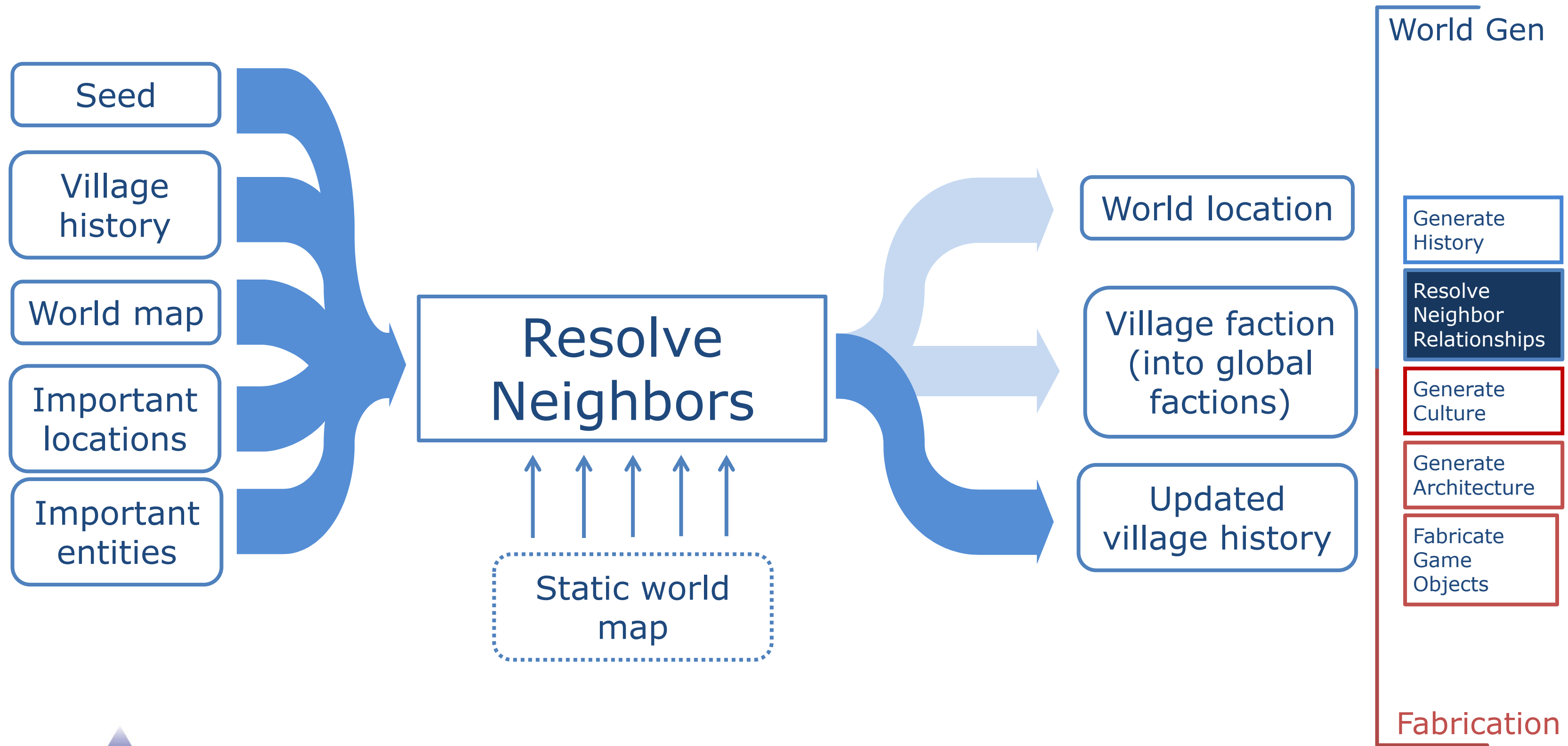
Resolve Neighbor Relationships

Generate Culture

Generate Architecture

Fabricate Game Objects

Fabrication



```
case 3:
// The village starts to worship a nearby legendary creature
// "The villagers of Uppar laid offerings at the feet of Tippur, legendary croc, in exchange for divine wisdom."

setEntityProperty("worships_creature", "*Worships.LegendaryCreature*");
addEntityListItem("sacredThings", "*Worships.LegendaryCreature.DisplayName*");
addEntityListItem("profaneThings", ExpandString("<spice.commonPhrases.profanity.!random> toward *Worships.LegendaryCreature.DisplayName*"));
addEntityListItem("itemAdjectiveRoots", "*Worships.LegendaryCreature.ShortDisplayName*");

gospel = String.Format(
    "The villagers of {0} laid offerings at the feet of {1} in exchange for {2} about {3}.|{4}",
    snapVillage.GetProperty("name"),
    "*Worships.LegendaryCreature.DisplayName*",
    ExpandString("<spice.commonPhrases.wisdom.!random>"),
    sacredThing,
    id
);
addEntityListItem("Gospels", gospel);
break;
```

Generate
HistoryResolve
Neighbor
RelationshipsGenerate
CultureGenerate
ArchitectureFabricate
Game
Objects

Fabrication


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case 3:
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    addEntityListItem("sacredThings", "*Worships.LegendaryCreature.DisplayName*");
    addEntityListItem("profaneThings", ExpandString("<spice.commonPhrases.profanity.!random> toward *Worships.LegendaryCreature.DisplayName*"));
    addEntityListItem("itemAdjectiveRoots", "*Worships.LegendaryCreature.ShortDisplayName*");

    gospel = String.Format(
        "The villagers of {0} laid offerings at the feet of {1} in exchange for {2} about {3}.|{4}",
        snapVillage.GetProperty("name"),
        "*Worships.LegendaryCreature.DisplayName*",
        ExpandString("<spice.commonPhrases.wisdom.!random>"),
        sacredThing,
        id
    );
    addEntityListItem("Gospels", gospel);
    break;
```

Generate
HistoryResolve
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Objects

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World Gen



Generate
History

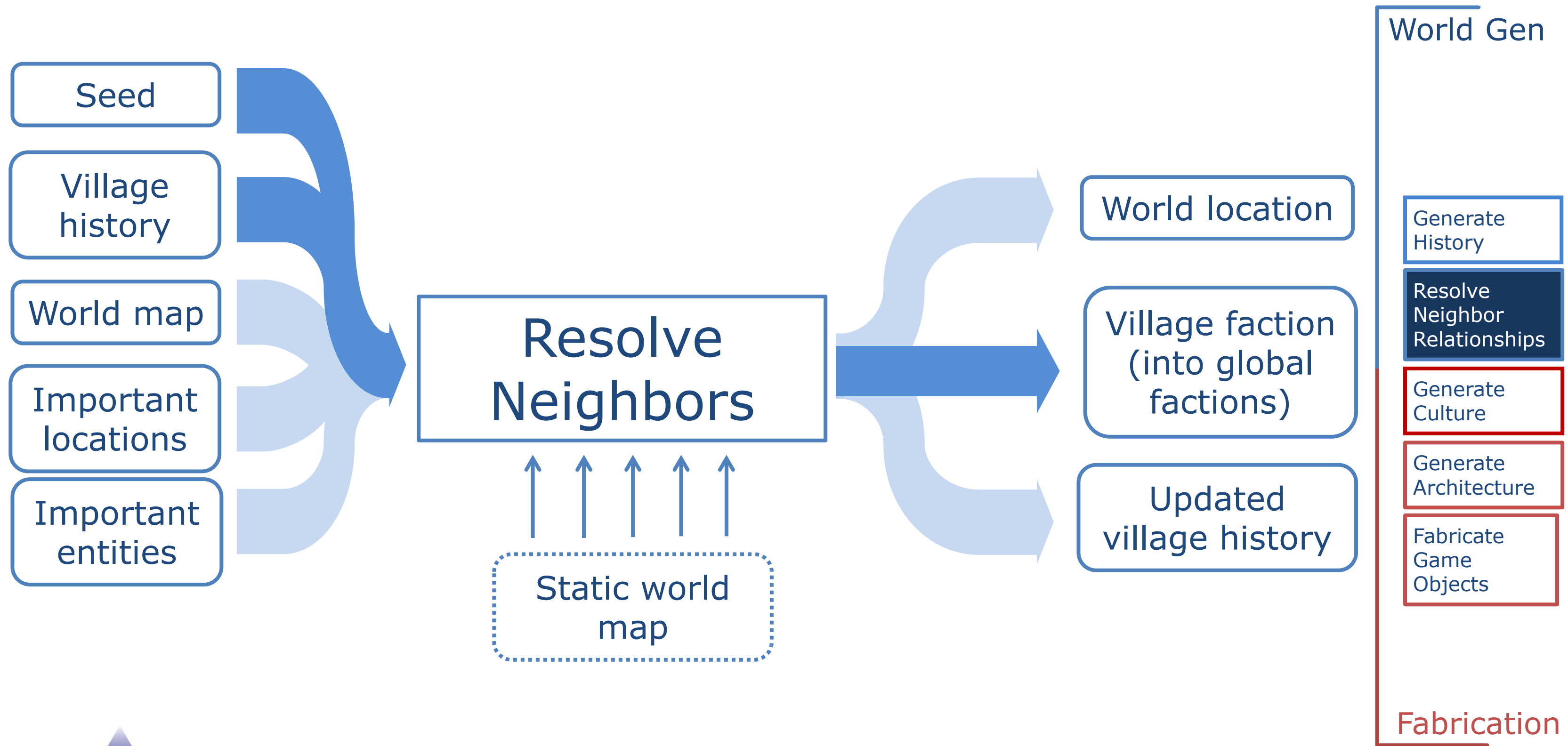
Resolve
Neighbor
Relationships

Generate
Culture

Generate
Architecture

Fabricate
Game
Objects

Fabrication



[Reputation]		ESC or 5 to exit
Faction	Reputation	
succulents	0	Succulents don't care about you, but aggressive ones will attack you.
Suhimian Cabal	-500	
swine	-475	You aren't welcome in their holy places.
tortoises	0	
trees	-300	
trolls	-475	
unshelled reptiles	-475	Succulents are interested in trading secrets about the locations in the salt dunes and sultans they admire or despise. They're also interested in hearing gossip that's about them.
urchins	-500	
villagers of Alammu	0	
villagers of Arquukish	0	
villagers of Binip	0	
villagers of Dashur	0	
villagers of Duarramrod	0	
villagers of Hawar	0	
villagers of Ibyshan	0	
villagers of Ilep	0	
villagers of Joppa	-140	
villagers of Kaggamor	0	
< 7 Equipment Quests 9 >		

Generate History

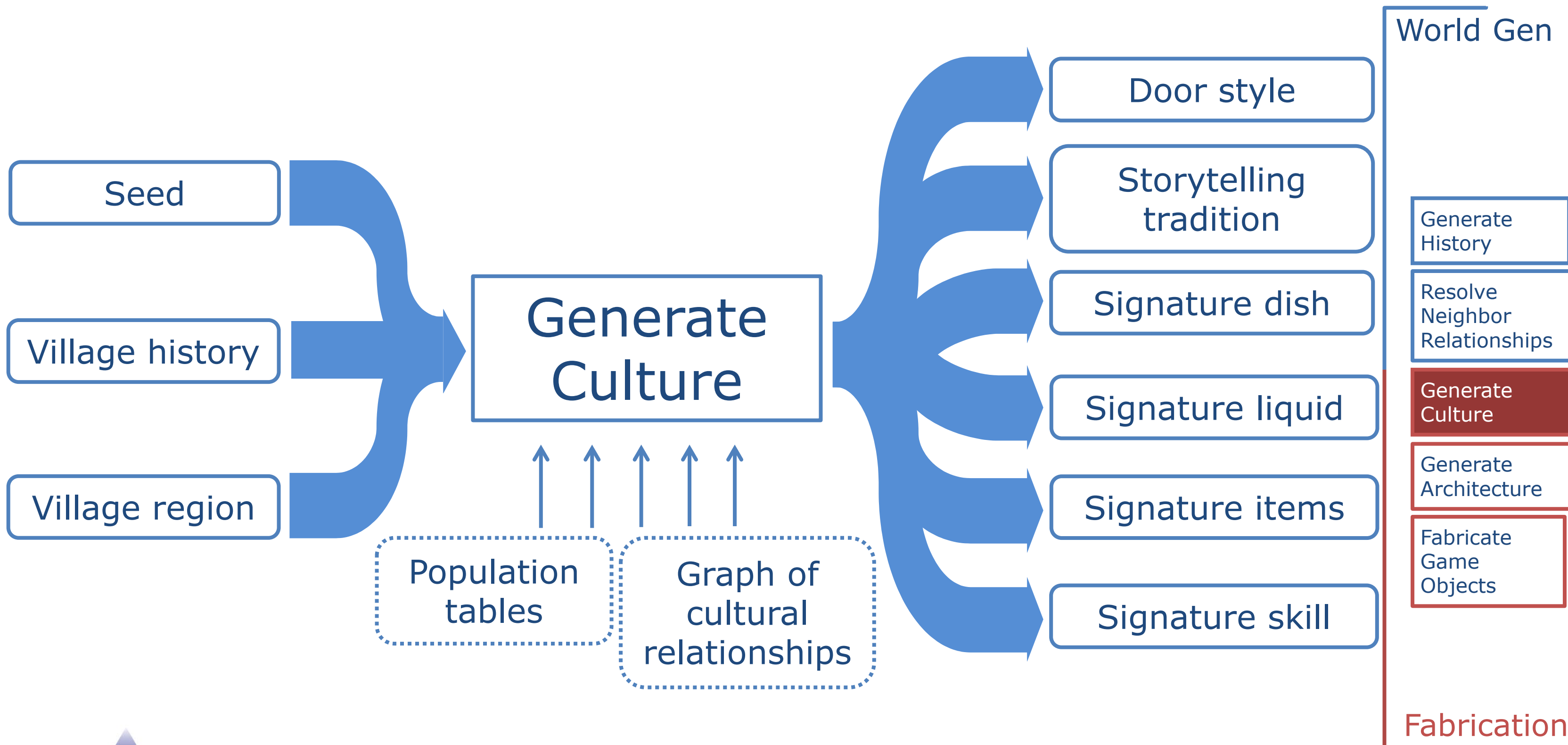
Resolve Neighbor Relationships

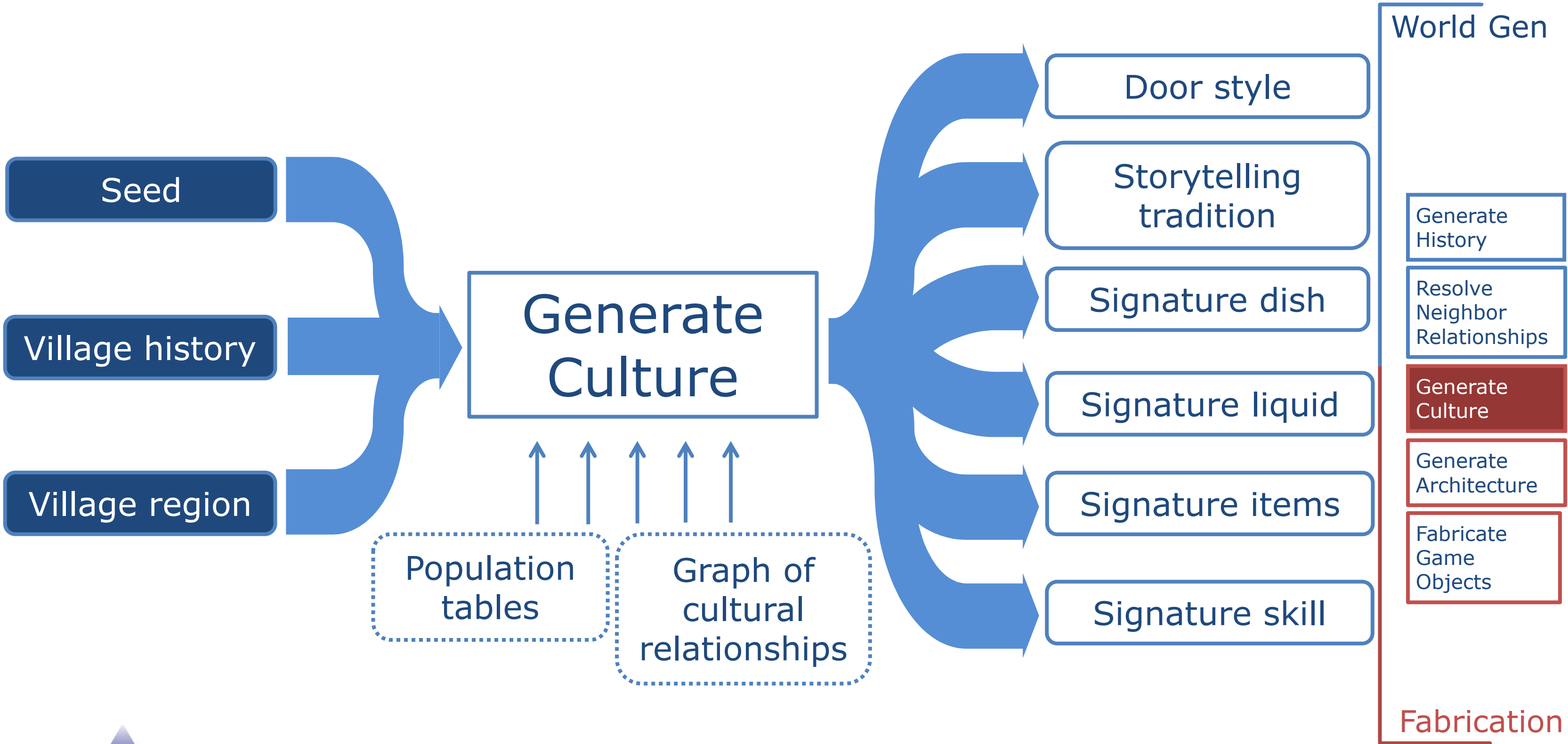
Generate Culture

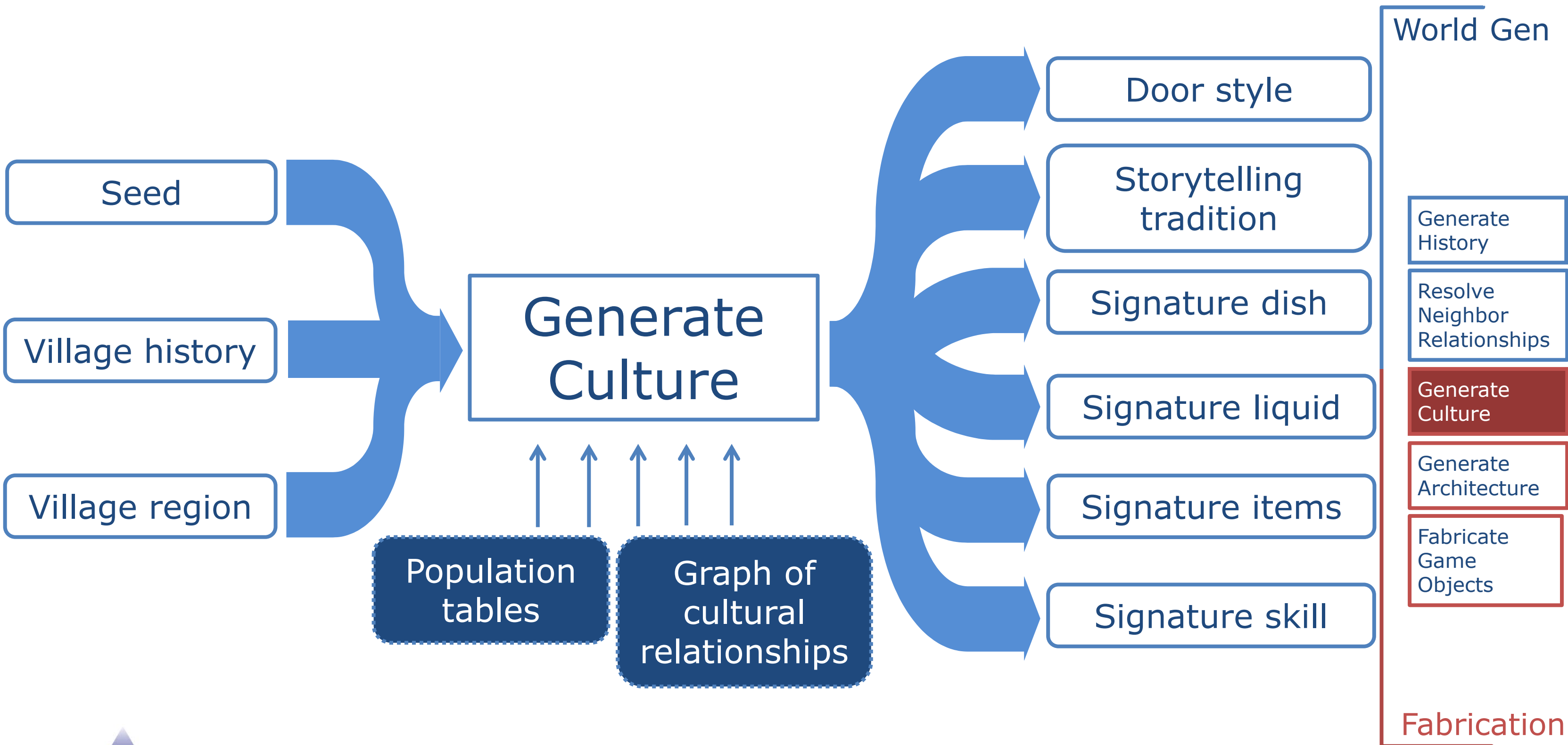
Generate Architecture

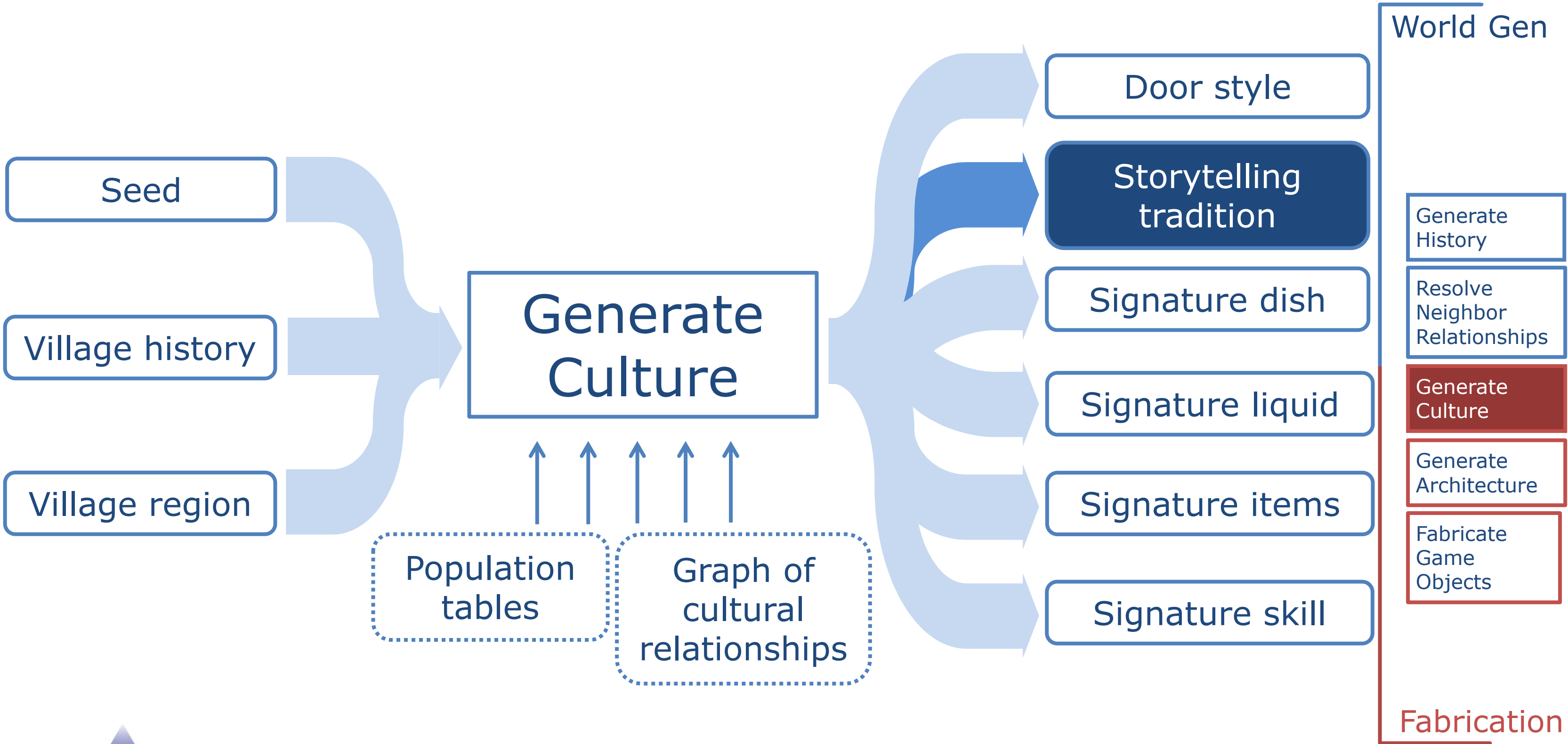
Fabricate Game Objects

Fabrication









Storytelling tradition



World Gen

Generate History

Resolve Neighbor Relationships

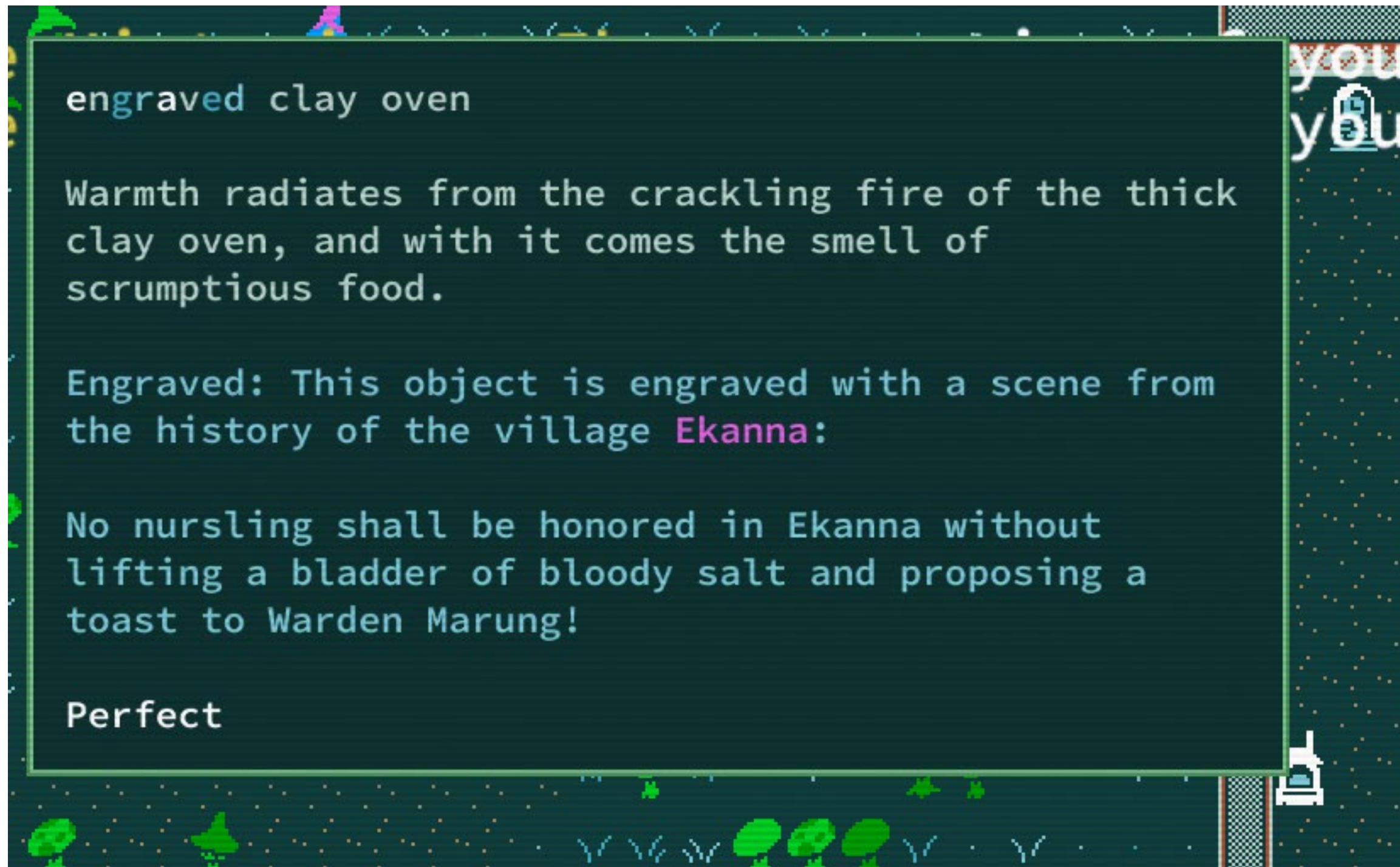
Generate Culture

Generate Architecture

Fabricate Game Objects

Fabrication

Storytelling tradition



World Gen

Generate
History

Resolve
Neighbor
Relationships

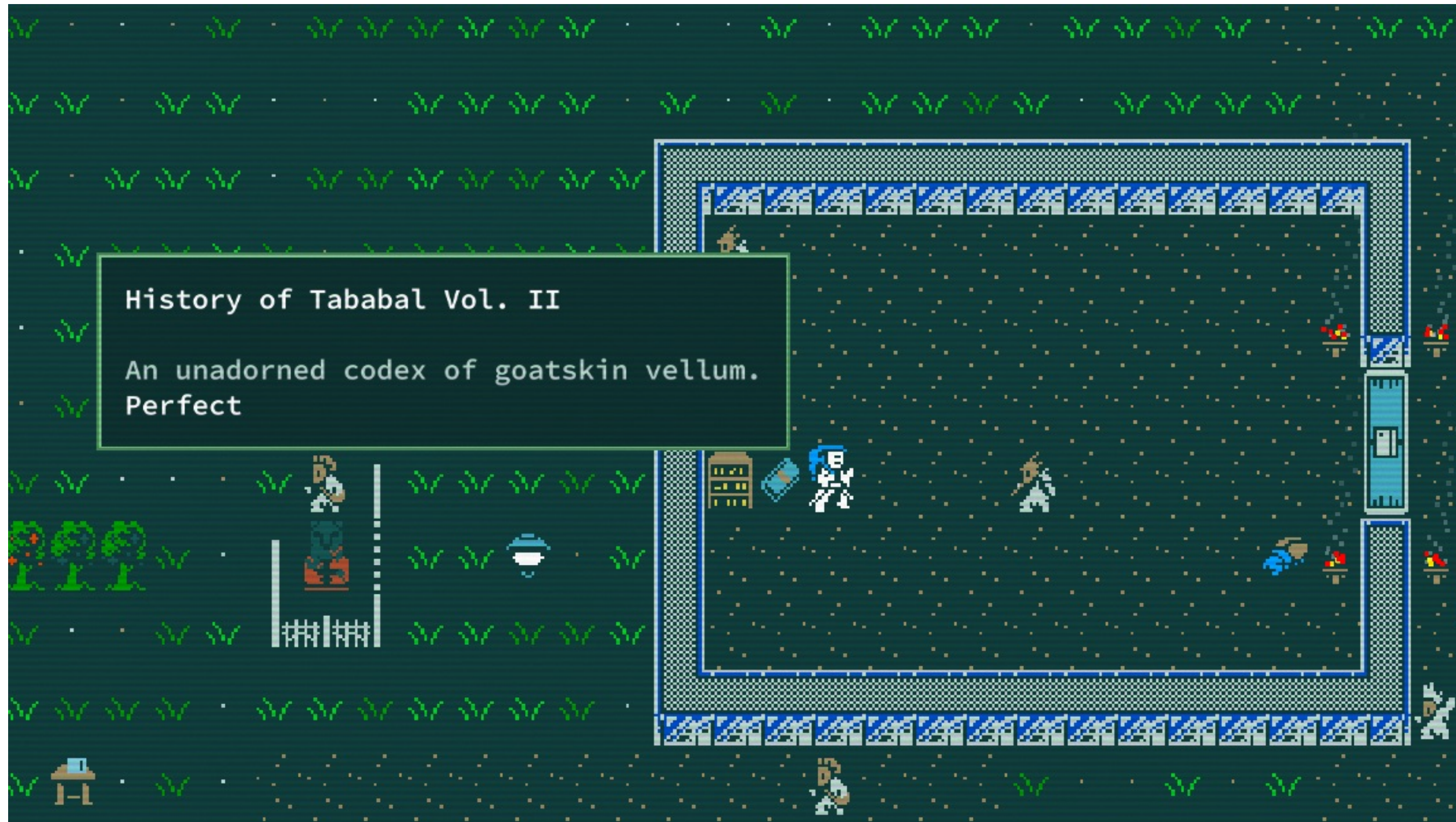
Generate
Culture

Generate
Architecture

Fabricate
Game
Objects

Fabrication

Storytelling tradition



World Gen

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History

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Generate
Culture

Generate
Architecture

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Game
Objects

Fabrication

Storytelling tradition

```
<population Name="Village_StorytellingTradition">
  <group Style="pickone">
    <object Blueprint="Doors" Weight="20"></object>
    <object Blueprint="Walls" Weight="20"></object>
    <object Blueprint="Vessels" Weight="20"></object>
    <object Blueprint="Furniture" Weight="20"></object>
    <object Blueprint="Monuments" Weight="40"></object>
    <object Blueprint="Historic Hall" Weight="20"></object>
    <object Blueprint="Books" Weight="15"></object>
    <object Blueprint="Library" Weight="15"></object>
    <object Blueprint="Graveyard" Weight="15"></object>
    <object Blueprint="Tattoo" Weight="10"></object>
    <object Blueprint="Holograms" Weight="10"></object>
  </group>
</population>
```

World Gen

Generate
History

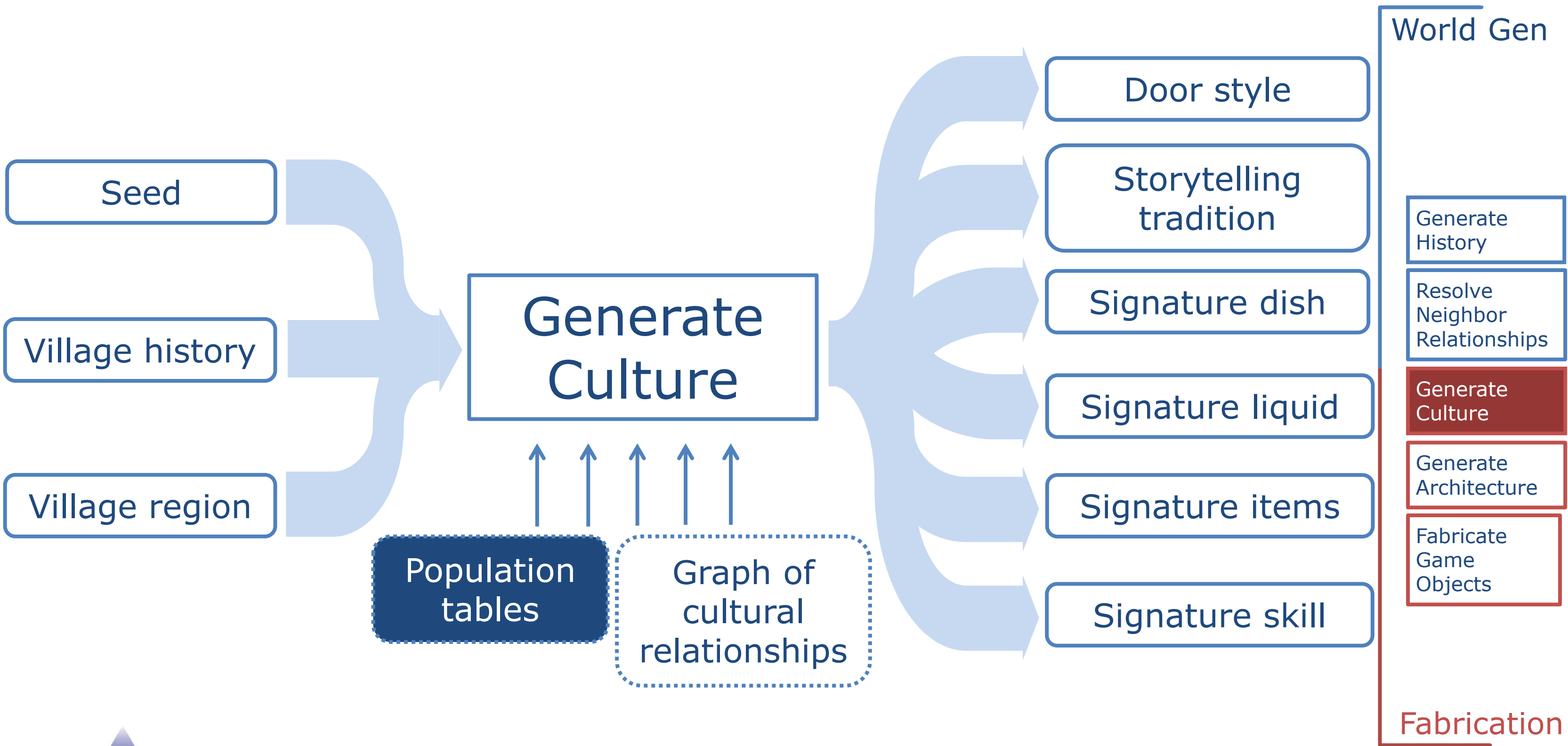
Resolve
Neighbor
Relationships

Generate
Culture

Generate
Architecture

Fabricate
Game
Objects

Fabrication



Population tables

```
<population Name="Village_StorytellingTradition">
  <group Style="pickone">
    <object Blueprint="Doors" Weight="20"></object>
    <object Blueprint="Walls" Weight="20"></object>
    <object Blueprint="Vessels" Weight="20"></object>
    <object Blueprint="Furniture" Weight="20"></object>
    <object Blueprint="Monuments" Weight="40"></object>
    <object Blueprint="Historic Hall" Weight="20"></object>
    <object Blueprint="Books" Weight="15"></object>
    <object Blueprint="Library" Weight="15"></object>
    <object Blueprint="Graveyard" Weight="15"></object>
    <object Blueprint="Tattoo" Weight="10"></object>
    <object Blueprint="Holograms" Weight="10"></object>
  </group>
</population>
```

World Gen

Generate
History

Resolve
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Culture

Generate
Architecture

Fabricate
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Objects

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Population tables

World Gen

```
<population Name="JungleCreatures">
  <group Style="pickone">
    <object Weight="5" Number="1" Blueprint="Boar"></object>
    <object Weight="5" Number="1" Blueprint="Salamander"></object>
    <object Weight="10" Number="1-3" Blueprint="GiantDragonfly"></object>
    <object Weight="10" Number="1" Blueprint="Ice frog"></object>
    <object Weight="15" Number="1" Blueprint="Albino ape"></object>
    <object Weight="5" Number="1" Blueprint="Horned Chameleon"></object>
    <object Weight="10" Number="1" Blueprint="Quillipede"></object>
    <object Weight="15" Number="1-3" Blueprint="Leech"></object>
    <object Weight="5" Number="1" Blueprint="Slumberling"></object>
  <group Style="pickeach" Weight="25">
    <object Number="1-2" Blueprint="Goatfolk Savage"></object>
    <object Chance="50" Number="1" Blueprint="Goatfolk Sower"></object>
    <object Chance="50" Number="1" Blueprint="Goatfolk Yurtwarden"></object>
    <object Chance="10" Number="1" Blueprint="Goatfolk Shaman"></object>
  </group>
</group>
</population>
```

Generate
History

Resolve
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Generate
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Fabricate
Game
Objects

Fabrication

Population tables

```
<population Name="AppleMerchantTentContents">
  <group Style="pickeach">
    <object Blueprint="Torchpost" Number="1-2" Hint="OutsideDoor:2"></object>
    <object Blueprint="Woven Basket" Number="1-2" Hint="InsideCorner"></object>
    <object Blueprint="Table" Number="0-2" Hint="AlongInsideWall"></object>
    <object Blueprint="Cider Vase" Number="2-3" Hint="AlongOutsideFrontWall"></object>
    <object Blueprint="Cider Vase" Number="1-2" Hint="AlongInsideWall"></object>
    <object Blueprint="Cider Bottle" Number="1-2" Hint="AlongInsideWall"></object>
    <object Blueprint="Cider Pitcher" Number="1-2" Hint="AlongInsideWall"></object>
  </group>
</population>
```

World Gen

Generate
History

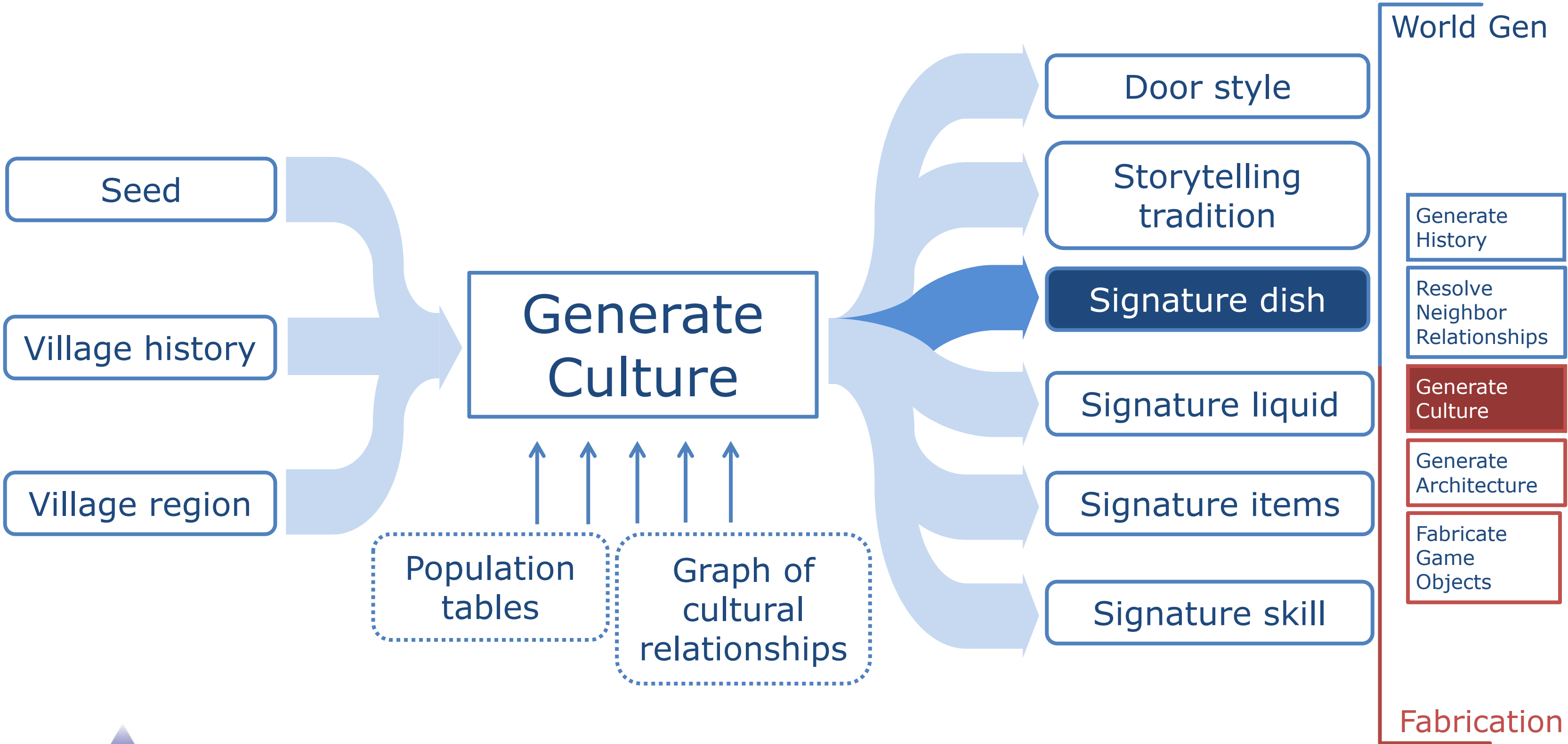
Resolve
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Fabrication



Signature dish

The fire breathes its warmth on your bones.

Eat Fungus and Electric Schnitzel with Goulash

Whip up a meal.

Choose ingredients to cook with.

Cook from a recipe.

Preserve your fresh foods.

World Gen

Generate
History

Resolve
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Signature dish

You start to metabolize the meal, gaining the following effect for the rest of the day:

75% chance that itchy skin doesn't develop into a fungal infection
+10 Electric Resist

Ok

World Gen

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Generate Architecture

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Signature dish

Viceroy 5-B-8A 385-F

Live and drink, friend.

Your reputation with the villagers of Sappur is 125.
Viceroy 5-B-8A 385-F can award an additional 100 reputation.

- 1) Share a secret with me, friend. [-50 reputation]
- 2) Would you teach me your ways? [learn Proselytize: -450 reputation]
- 3) What a savory smell! Teach me to cook the favorite dish of Sappur.
[learn to cook Fungus and Electric Schnitzel with Goulash: -50 reputation]
- 4) I would ask you to join me, friend. [-848 reputation] [End]
- 5) Live and drink, friend. [end the water ritual]

World Gen

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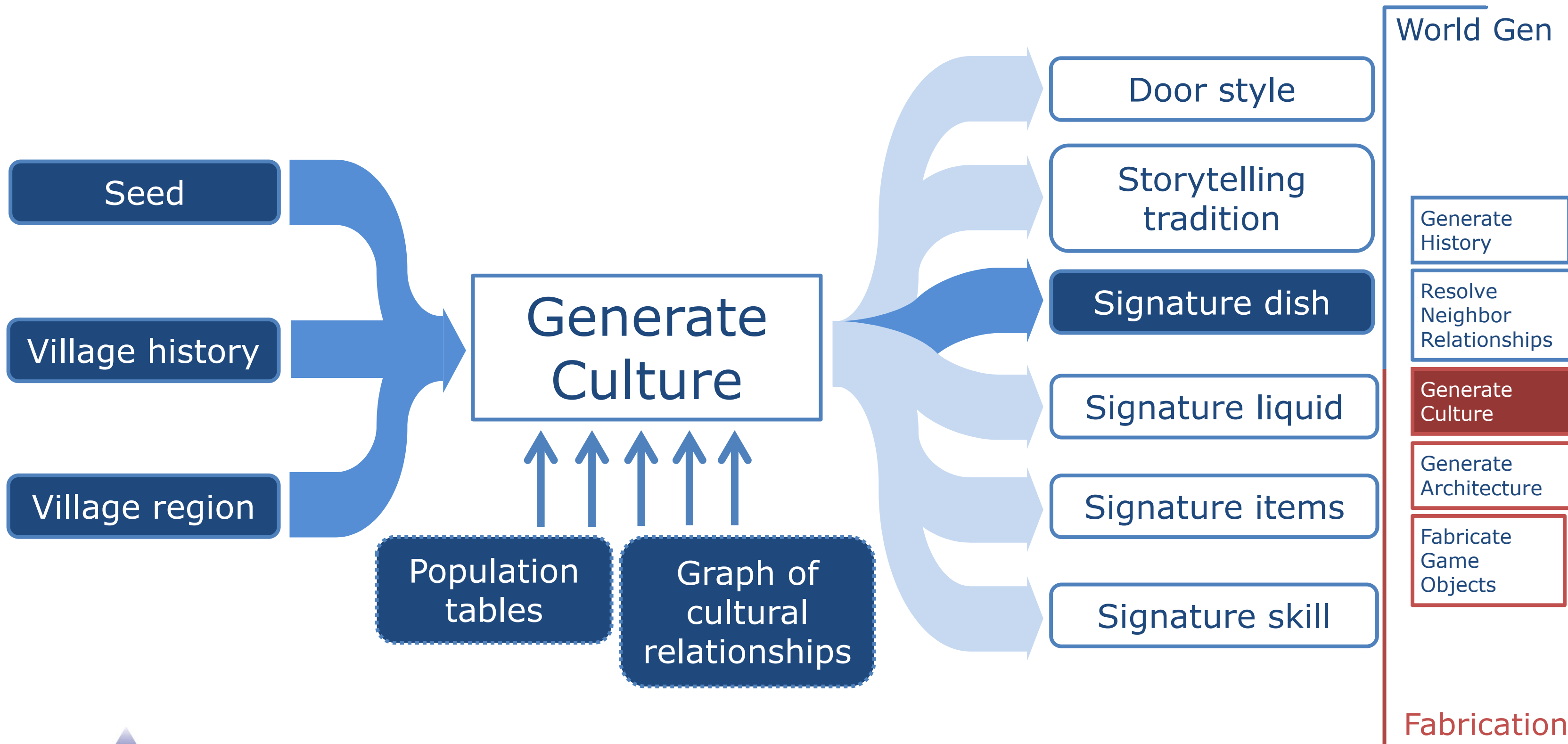
Resolve
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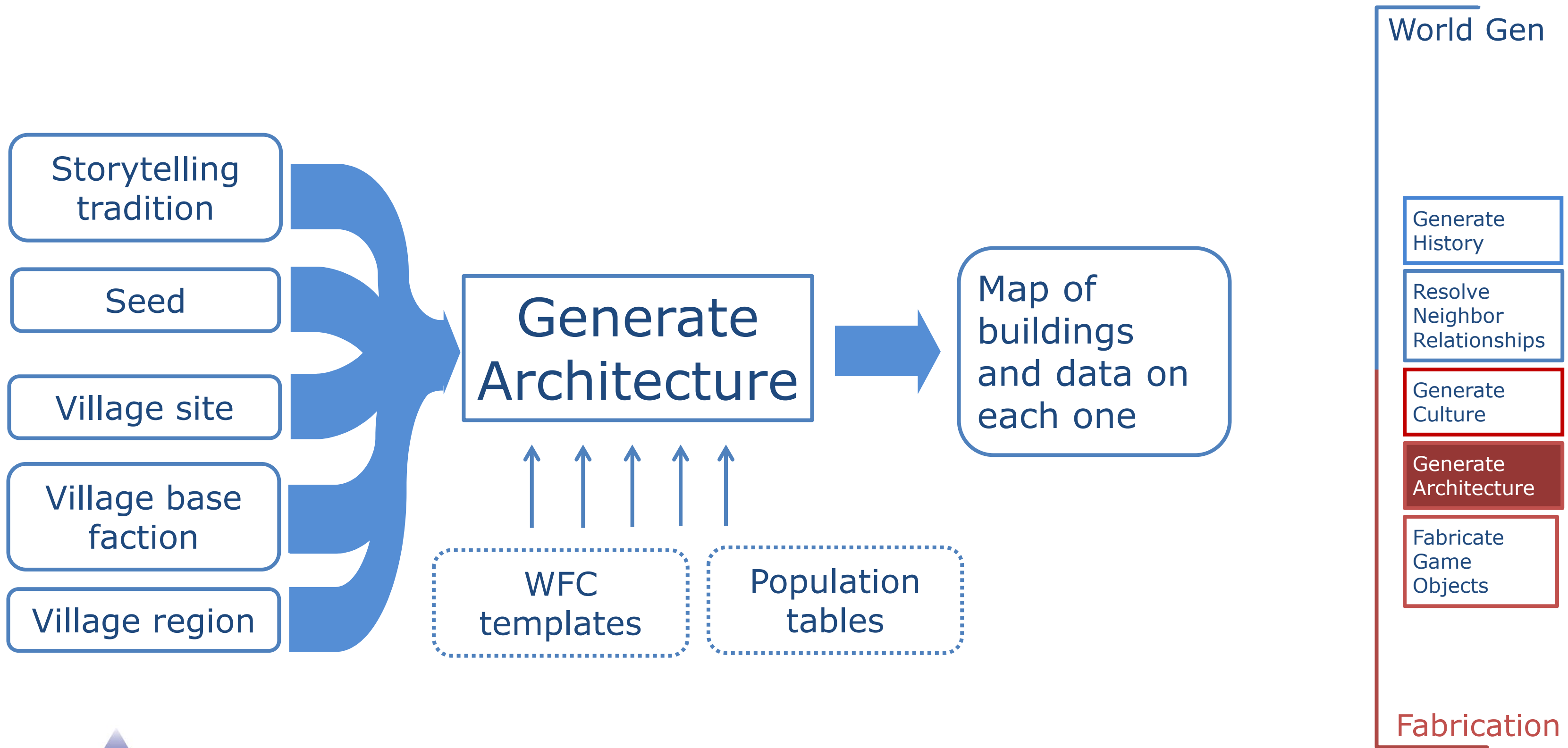
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Prefabrication Decision Points

1. Building style
2. Important buildings
3. Agricultural plants
4. Decorative plants
5. Wild plants
6. Liquids
7. Door style
8. Wall types

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Village base
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Population tables

```
<population Name="Villages_BuildingStyle_Default">
  <group Style="pickone">
    <object Blueprint="wfc,huts12"></object>
    <object Blueprint="squarehut"></object>
    <object Blueprint="roundhut"></object>
    <object Blueprint="tent"></object>
  </group>
</population>

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  <group Style="pickone">
    <object Weight="1" Blueprint="wfc"></object>
    <object Weight="1" Blueprint="squarehut"></object>
    <object Weight="1" Blueprint="roundhut"></object>
    <object Weight="97" Blueprint="tent"></object>
  </group>
</population>
```

```
<population Name="Villages_BuildingStyle_Faction_Birds">
  <group Style="pickone">
    <object Blueprint="aerie"></object>
  </group>
</population>

<population Name="Villages_BuildingStyle_Faction_Fish">
  <group Style="pickone">
    <object Blueprint="pond"></object>
    <object Blueprint="islandpond"></object>
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  </group>
</population>

<population Name="Villages_BuildingStyle_Faction_Mollusks">
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    <object Blueprint="islandpond"></object>
    <object Blueprint="walledpond"></object>
  </group>
</population>
```

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1. Building style
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Important buildings



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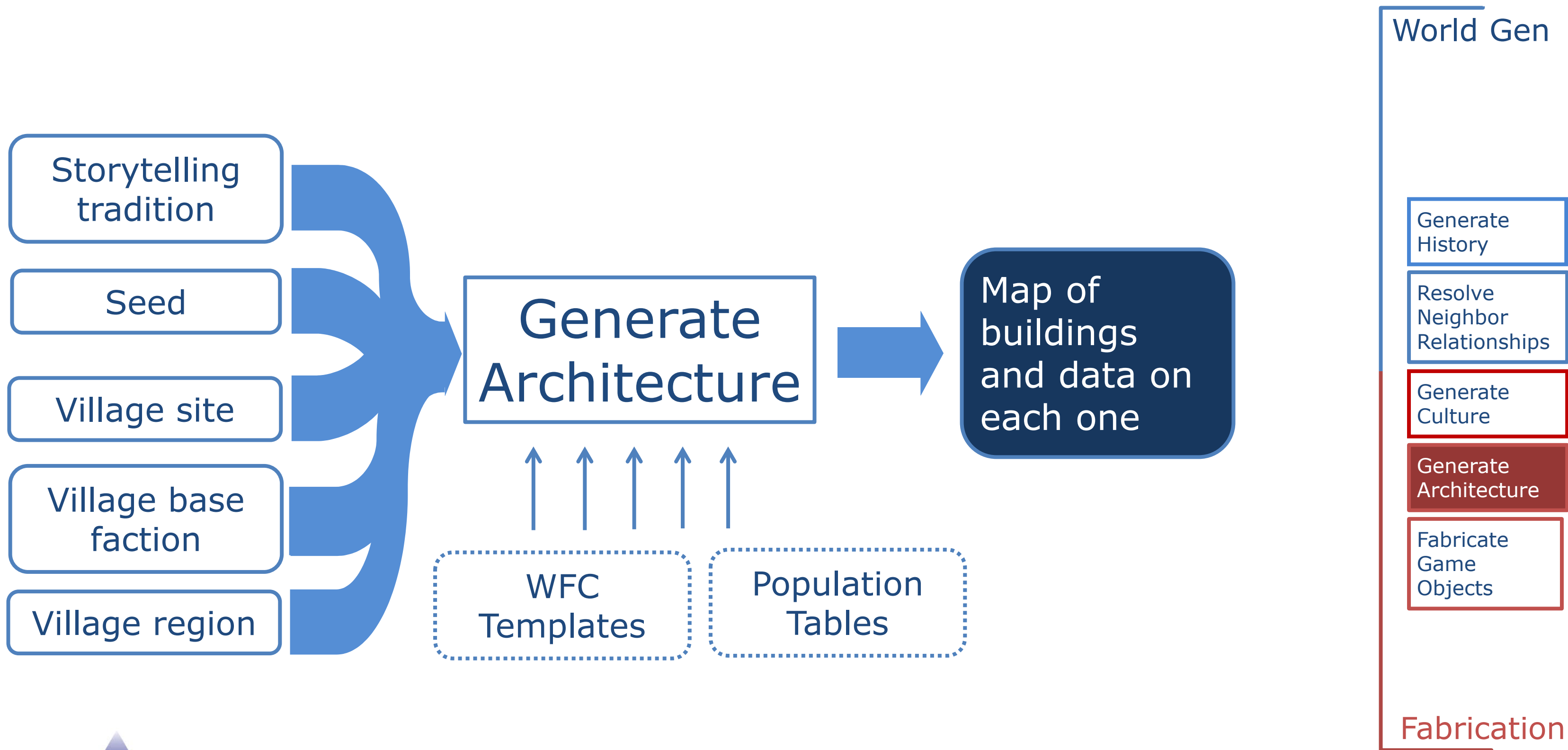
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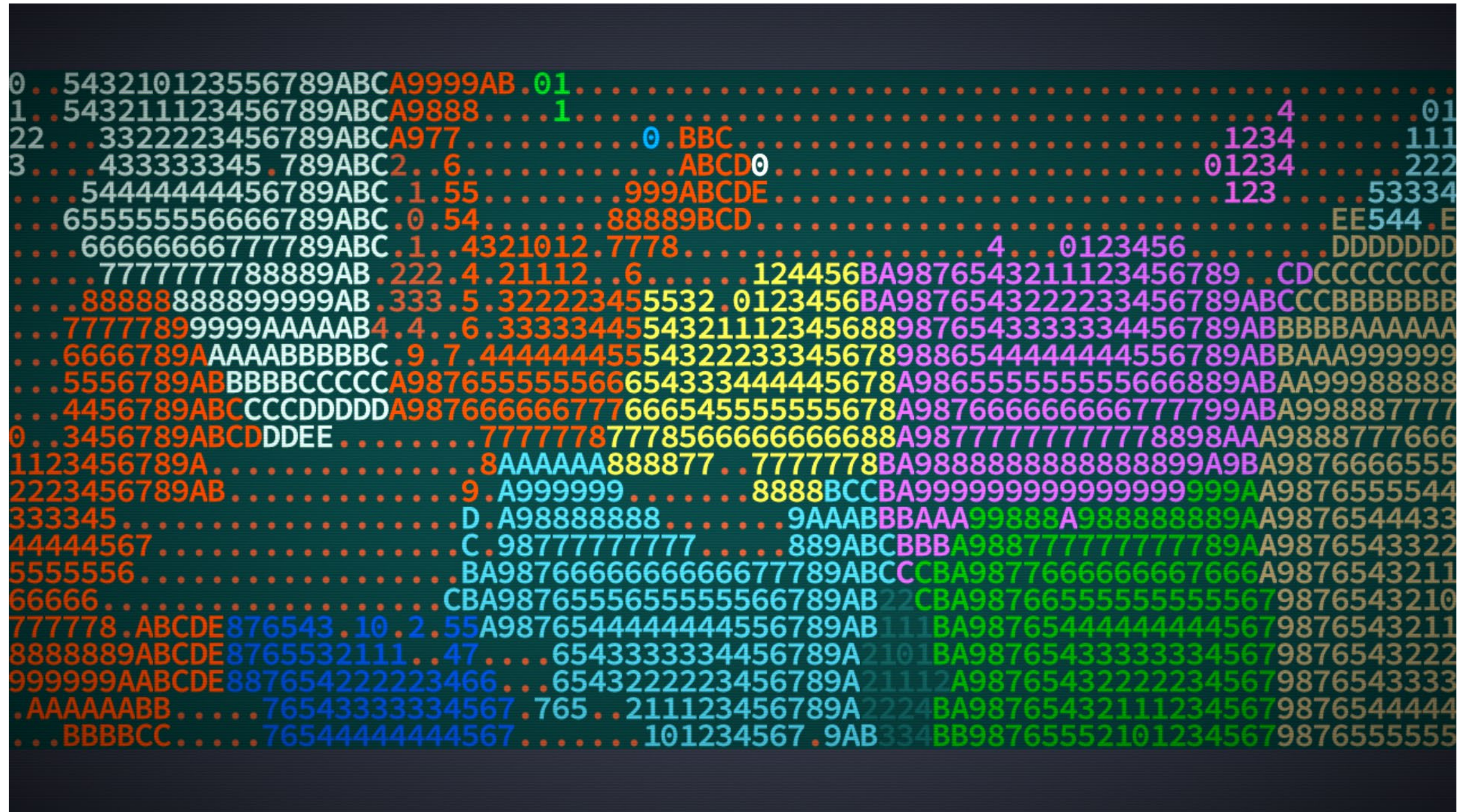
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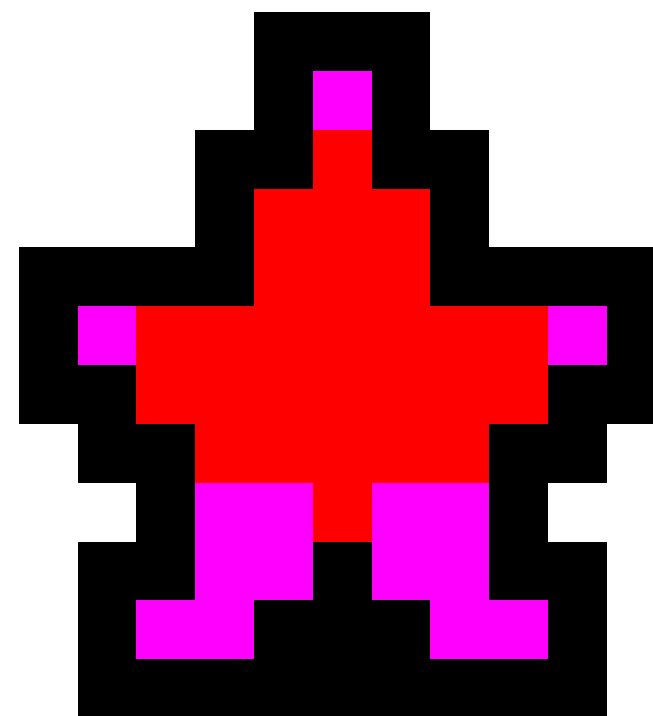
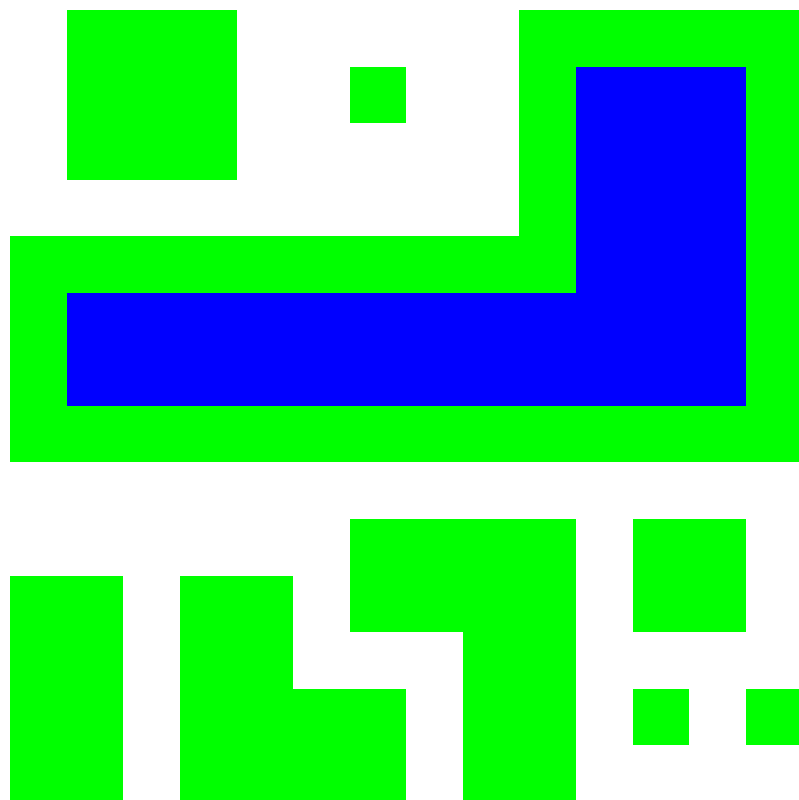
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WFC
templates



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[illegible]

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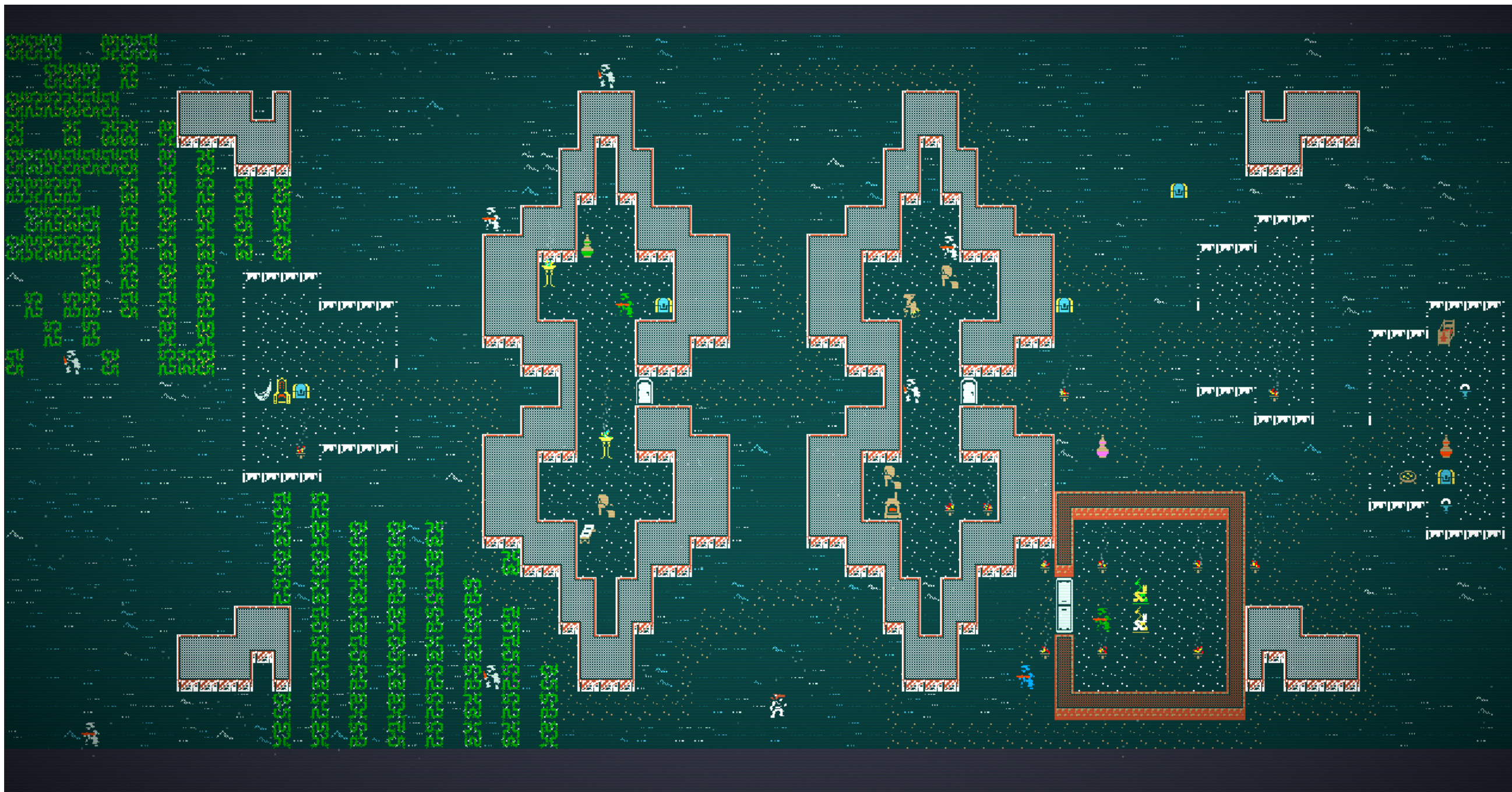
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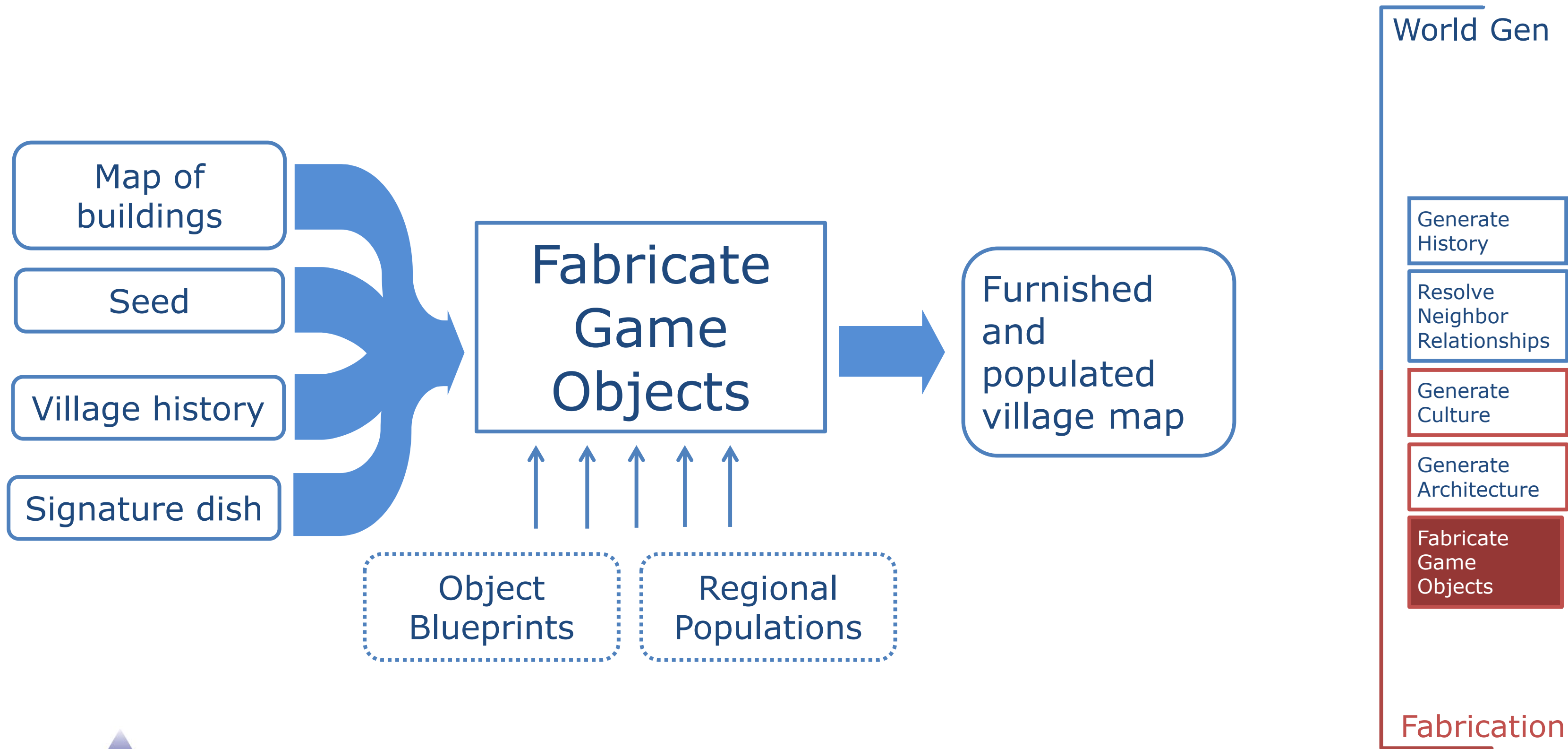
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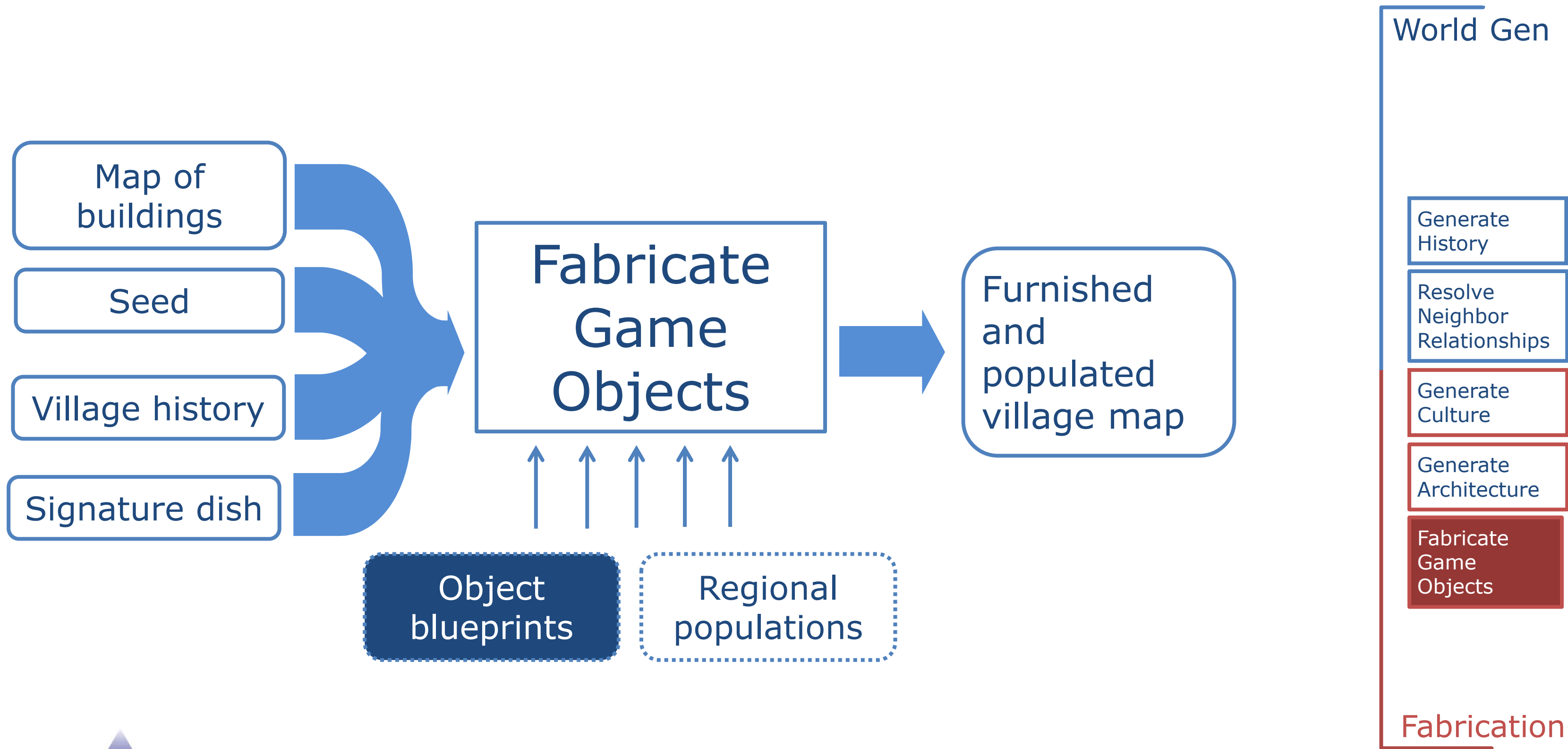
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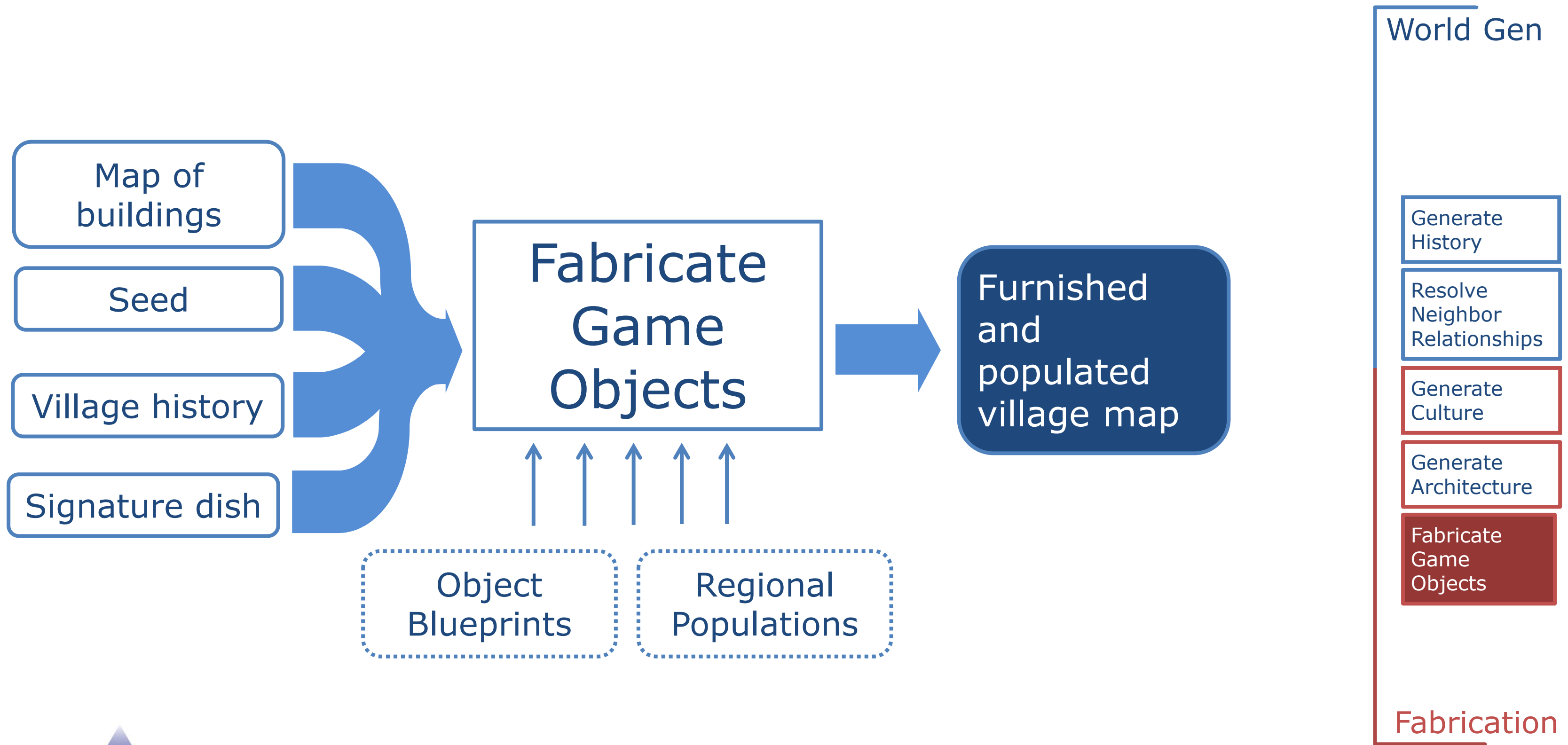


Object blueprints

```
<object Name="Torchpost" Inherits="NotakeFurniture">
  <part Name="Render" DisplayName="torch sconce" RenderString="249" ColorString="&R" DetailColor="w" />
  <part Name="Physics" Weight="13" Takeable="false" Solid="false" />
  <part Name="AnimatedMaterialFire"></part>
  <part Name="LightSource" Lit="true" Radius="6"></part>
  <part Name="Description" Short="A brightly burning torch in a sconce."></part>
  <part Name="Metal"></part>
  <intproperty Name="Inorganic" Value="1" />
  <part Name="UnityPrefabImposter" PrefabID="Prefabs/Particles/TorchpostFlames"></part>
  <intproperty Name="NavigationWeight" Value="95" />
  <stag Name="LightSource"></stag>
</object>
```

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Furnished and populated village map



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Furnished and populated village map



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Furnished and populated village map



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Furnished and populated village map

Queen Ptebesis the Great

Welcome to the village of Qalep, adventurer. Here you will find shade and vittle, along with other provisions to help you better scour the rust-caves for treasure. Come what may, you may drink of our freshwater and quench your thirst.

Resorbing matter is no way to bless the queen.

1) I'm looking for work.

2) Your thirst is mine, my water is yours. [begin water ritual; 1 dram of water]

3) Let's trade. [begin trade]

4) Live and drink, friend. [End]

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Furnished and populated village map

Magelseshrub

Traveler, we've been speaking to jewelers and we came upon a nearby location forgotten to our people, Yellow Mimor. What pearls might this place contain? Carbon dioxide? Ample sunlight? A shrine to the practice of shield slamming? We must know. If you locate it for us, we will compensate you for your service. What do you think? We hear it's located somewhere between 3 and 7 parasangs east of Iwan.

1) Yes. I will locate Yellow Mimor as you ask. [Accept Quest] [End]

2) No, I will not. [End]

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Takeaways

- Think carefully about your design context
- Lean into modularity
- Use abstraction to your advantage
- Parameterize your modules
- Build expressive tools like population tables



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