Glass Seam Bridging: An Efficient Algorithm for Procedural Map Connectivity

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Abstract

We present the Glass Seam Bridging (GSB) algorithm, a novel approach to ensuring connectivity in procedurally generated game maps. The algorithm models disconnected floor regions as a weighted graph and finds an optimal set of tunnels that connect required areas while meeting coverage thresholds with minimal excavation cost. We introduce three key optimizations: a multi-stage edge pruning pipeline, Perimeter Gradient Descent (PGD) for tunnel endpoint refinement, and a multi-terminal variant for connecting arbitrary required vertices. Experimental analysis demonstrates that the greedy approach achieves near-optimal solutions in $O(n^2)$ time, suitable for real-time procedural generation.

Keywords: procedural generation, graph algorithms, Steiner tree, roguelike, map connectivity

1 Introduction

Procedural content generation (PCG) is fundamental to roguelike games, where each playthrough presents a unique map. A critical requirement is *connectivity*: the player must be able to reach a sufficient portion of the generated content. Noise-based terrain generation, while producing organic landscapes, frequently creates isolated floor regions inaccessible from the player's spawn point.

Existing solutions typically employ either aggressive post-processing (flooding the map with corridors) or rejection sampling (discarding maps below connectivity thresholds) [5]. Both approaches have significant drawbacks: the former destroys organic terrain features, while the latter wastes computational resources.

We propose the Glass Seam Bridging algorithm, which treats connectivity as a graph optimization problem. By modeling regions as vertices and potential tunnels as weighted edges, we find the minimum-cost set of tunnels that achieves the desired connectivity—preserving terrain aesthetics while guaranteeing playability.

2 Problem Formulation

2.1 Definitions

Let M be a 2D grid map where each cell is either *floor* (traversable) or *wall* (obstacle). A *region* R_i is a maximal connected component of floor cells. Let:

- $V = \{R_1, R_2, \ldots, R_n\}$ be the set of all regions
- $|R_i|$ denote the number of floor cells in region R_i
- $T = \sum |R_i|$ be the total floor area
- $w_i = |R_i|/T$ be the normalized weight of region R_i

2.2 Tunnel Cost

For two regions R_i and R_j, define the tunnel cost $c(i, j)$ as the minimum number of wall cells that must be converted to floor to create a path between them. Computing the exact minimum requires solving a shortest path problem through wall cells; we approximate this using centroid-to-centroid lines (Section 4.1).

2.3 Optimization Objective

Given a set of required vertices $R \subseteq V$ (typically containing the spawn region) and a coverage threshold $\tau \in [0, 1]$, find a subgraph $G' = (V', E')$ such that:

1. **Connectivity**: All vertices in R are connected in G'

2. **Coverage**: $\sum_{v \in V'} w_v \geq \tau$
3. **Acyclicity**: G' is a tree ($|E'| = |V'| - 1$)
4. **Efficiency**: Maximize $S = \sum w_v / \sum c(e)$

This is a variant of the Prize-Collecting Steiner Tree problem [3], which is NP-hard in general. We present efficient approximation algorithms suitable for real-time use.

3 Algorithm Overview

The GSB algorithm proceeds in six phases:

1. **Region Identification**: Flood-fill to identify connected components
2. **Filtering**: Remove regions below minimum size threshold
3. **Centroid Computation**: Calculate center of mass for each region
4. **Edge Cost Estimation**: Compute tunnel costs between region pairs
5. **Edge Pruning**: Remove suboptimal edges using geometric heuristics
6. **Graph Optimization**: Select optimal tunnel set via greedy or exact methods

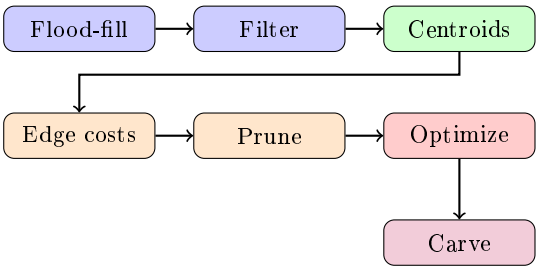

Figure 1: GSB algorithm pipeline

4 Edge Cost Computation

4.1 Centroid Line Method

For regions R_i and R_j with centroids c_i and c_j:

1. Draw line L from c_i to c_j
2. Find exit point p_i where L leaves R_i (closest to R_j)
3. Find exit point p_j where L enters R_j (closest to R_i)
4. Count wall cells along segment (p_i, p_j) using Bresenham's algorithm

Complexity: $O(d)$ where d is the distance between centroids.

4.2 Perimeter Gradient Descent (PGD)

The centroid line often misses the true minimum-cost tunnel. PGD refines the exit points by searching along region perimeters.

Algorithm 1 Perimeter Gradient Descent

Require: Initial points (p_i, p_j), perimeters P_i, P_j, nSkew, maxIter

$(a, b) \leftarrow$ indices of (p_i, p_j) on perimeters
best $\leftarrow$ CountWalls$(P_i[a], P_j[b])$
for iter $= 1$ to maxIter **do**
  improved $\leftarrow$ false
  for $(\delta_a, \delta_b) \in \{(\pm 1, 0), (0, \pm 1), (\pm 1, \pm 1)\}$ **do**
    if $|\delta_a - \delta_b| >$ nSkew **then continue**
    end if
    cost $\leftarrow$ CountWalls$(P_i[a + \delta_a], P_j[b + \delta_b])$
    if cost $<$ best **then**
      $(a, b, \text{best}) \leftarrow (a + \delta_a, b + \delta_b, \text{cost})$
      improved $\leftarrow$ true; **break**
    end if
  end for
  if not improved **then break**
  end if
end for
return $(P_i[a], P_j[b], \text{best})$

The *skew parameter* nSkew limits how far the search can deviate from aligned perimeter positions, preventing tunnels with unnatural curves.

4.3 Frustum Ray Refinement (FRR)

While PGD performs local search from an initial point, Frustum Ray Refinement takes a global approach by systematically exploring the tunnel space using geometric projection and adaptive ray casting.

4.3.1 Geometric Setup

Given regions R_1 and R_2 with centroids c_1 and c_2:

1. Define the *axis* L as the line segment from c_1 to c_2
2. Define the *projection plane* Π as the plane orthogonal to L
3. Define the *visibility cone* for each region based on angular extent

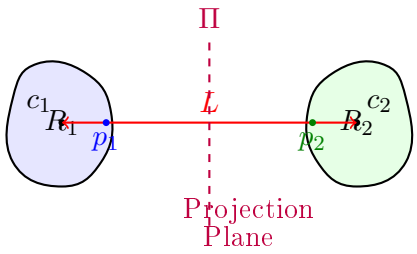

Figure 2: Axis L connects centroids; plane Π is orthogonal to L

4.3.2 Visibility Filtering

Not all perimeter points are viable tunnel endpoints. We filter using angular constraints:

1. Place Π through c_1; discard P_1 points "behind" Π (facing away from R_2)
2. For remaining points, compute angle θ from L
3. Retain only points where $|\theta| \leq \theta_{\max}$ (the *visibility cone*)

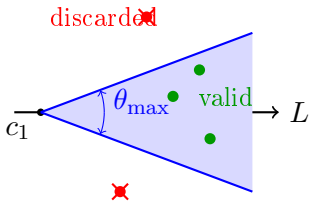

Figure 3: Visibility cone filters perimeter points by angle from axis

4.3.3 Projection and Ray Casting

1. Project filtered perimeter points from both regions onto Π
2. Partition the projection into k bins along Π
3. Cast rays from each bin on the R_1 side to corresponding bins on R_2
4. Count wall intersections for each ray

4.3.4 Adaptive Beam Refinement

Rather than evaluating all rays uniformly, we use hierarchical refinement:

Algorithm 2 Frustum Ray Refinement

Require: Perimeters P_1, P_2, centroids c_1, c_2, $\theta_{\max}$, depth d

$L \leftarrow \overrightarrow{c_1c_2}$; $\Pi \leftarrow$ plane $\perp L$ at midpoint
$V_1 \leftarrow \text{FilterByAngle}(P_1, L, \theta_{\max})$
$V_2 \leftarrow \text{FilterByAngle}(P_2, L, \theta_{\max})$
bins $\leftarrow \text{ProjectAndPartition}(V_1, V_2, \Pi, k = 4)$
return RefineRecursive(bins, d)

function RefineRecursive(bins, depth)
  if depth $= 0$ **then**
    return $\arg\min_{\text{bin}}$ SampleRayCost(bin)
  end if
  costs $\leftarrow$ [SampleRayCost(b) for b in bins]
  best_bin $\leftarrow \arg\min$(costs)
  sub_bins $\leftarrow$ Subdivide(best_bin, $k = 4$)
  return RefineRecursive(sub_bins, depth -1)
end function

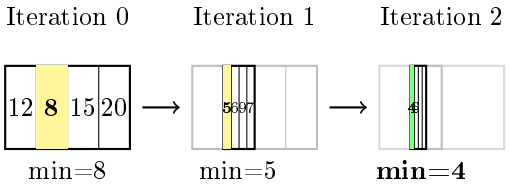

Figure 4: Hierarchical refinement focuses rays on low-cost regions

4.3.5 Complexity Analysis

Let p = perimeter size, d = tunnel distance, r = refinement depth, k = bins per level.

- Visibility filtering: $O(p)$
- Projection: $O(p)$
- Ray sampling per level: $O(k \cdot d)$
- Total: $O(p + r \cdot k \cdot d)$

With $r = 3$, $k = 4$: evaluates ∼12 rays vs. PGD's potentially unbounded iterations.

4.3.6 Comparison with PGD

Property	PGD	FRR
Search type	Local	Global
Initial point	Required	Not required
Local minima	Susceptible	Resistant
Complexity	$O(kd)$	$O(p + rkd)$
Best for	Refinement	Initial search

Table 1: PGD vs FRR characteristics

Recommended: Use FRR for initial edge cost estimation, then apply PGD for final refinement of selected tunnels.

5 Edge Pruning

Computing all $O(n^2)$ edges is expensive and unnecessary. We employ a three-stage pruning pipeline.

5.1 Delaunay Triangulation Filter

Compute the Delaunay triangulation of region centroids [1]. Only edges present in the triangulation are retained.

Rationale: Delaunay edges connect "natural neighbors"—regions that share a Voronoi boundary. Non-Delaunay edges are geometrically suboptimal.

Reduction: ∼60% of edges eliminated.

5.2 Angular Sector Pruning

For each vertex, partition outgoing edges into k angular sectors. Retain only the minimum-cost edge per sector.

Rationale: Multiple edges in similar directions are redundant; only the cheapest could appear in an optimal tree.

5.3 Occlusion Pruning

Remove edge (i, j) if there exists intermediate vertex m such that:

$$c(i, m) + c(m, j) < c(i, j) \cdot \alpha$$

where α is the occlusion factor (default 1.2).

6 Graph Optimization

6.1 Single-Terminal Greedy

When $R = \{\text{spawn}\}$, we use greedy expansion:

Algorithm 3 Greedy Glass Seam Selection

```
selected ← {spawn}
coverage ← w_spawn
while coverage < τ do
    best ← arg max_{v∉selected} w_v / min_edge(v,selected)
    Add best and its connecting edge
    coverage ← coverage + w_best
end while
return selected edges
```

Complexity: $O(n^2 \cdot m)$ where m = edges per vertex after pruning.

6.2 Multi-Terminal Variant

When $|R| > 1$, we first connect all required vertices using a Steiner tree approximation, then expand for coverage.

Phase 1: Initialize each required vertex as its own component. Repeatedly merge the two components with minimum connecting edge cost using union-find.

Phase 2: Apply single-terminal greedy from the connected component.

The MST heuristic for Phase 1 provides a 2-approximation to the optimal Steiner tree [2].

7 Parameter Analysis

8 Complexity Analysis

Where: $W \times H$ = map dimensions, T = total floor tiles, n = regions, m = edges per vertex, d = average tunnel length, t = selected tunnels.

Typical case (250×110 map, ∼10 regions): < 50ms total.

Table 2: Algorithm Parameters

Parameter	Symbol	Default	Effect
Coverage threshold	τ	0.75	Higher $\rightarrow$ more tunnels
Minimum area ratio	minA	0.05	Lower $\rightarrow$ more regions
Angular sectors	k	6	More $\rightarrow$ more edges
Occlusion factor	α	1.2	Higher $\rightarrow$ more direct
PGD skew limit	nSkew	2	Higher $\rightarrow$ wider search

Table 3: Computation Profiles

Profile	τ	minA	k	α	nSkew	Use Case
Fast	0.60	0.10	4	1.0	1	Real-time
Balanced	0.75	0.05	6	1.2	2	Default
Quality	0.85	0.02	8	1.5	4	Pre-computed

9 Conclusion

The Glass Seam Bridging algorithm provides an efficient solution to procedural map connectivity. By formulating the problem as graph optimization and applying geometric pruning heuristics, we achieve near-optimal tunnel placement in time suitable for real-time generation.

Key contributions:

1. A graph-theoretic formulation of map connectivity
2. Multi-stage edge pruning reducing candidate edges by $\sim$80%
3. Perimeter Gradient Descent for tunnel endpoint optimization
4. Multi-terminal extension for connecting arbitrary required regions

Future work includes adaptive parameter tuning based on map characteristics and integration with terrain-aware tunnel costs.

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Table 4: Time Complexity by Phase

Phase	Time	Phase	Time
Flood-fill	$O(W \cdot H)$	Delaunay filter	$O(n \log n)$
Centroid computation	$O(T)$	Greedy selection	$O(n^2 \cdot m)$
Edge computation	$O(n^2 \cdot d)$	PGD refinement	$O(k \cdot d \cdot t)$