In[185]:=

```
rcc3DStep[g_Graph] := Module[{allEdges, activeEdges, e1,
    e2, x, y, z, w, nextV, newActiveEdges, inertEdges, selectedPair},
 allEdges = EdgeList[g];
 activeEdges = Cases[allEdges, _UndirectedEdge];

 (* 如果活性边不足，停止 *)
 If[Length[activeEdges] < 2, Return[g]];

 (* 蒙特卡洛采样：寻找共点边 *)
 Block[{shuffled = RandomSample[activeEdges]},
  Do[
   e1 = shuffled[[i]];
   (* 局部搜索，向后看 30 个邻居 *)
   Do[
    e2 = shuffled[[j]];
    (* 共点检查 *)
    If[Length[Intersection[List @@ e1, List @@ e2]] == 1,
     selectedPair = {e1, e2}; Goto["Found3D"];
    ], {j, i + 1, Min[i + 30, Length[shuffled]]}
   ], {i, 1, Length[shuffled]}
  ]
 ];

 Label["Found3D"];
 If[Not[ValueQ[selectedPair]], Return[g]];

 {e1, e2} = selectedPair;
 y = Intersection[List @@ e1, List @@ e2][[1]];
 x = Complement[List @@ e1, {y}][[1]];
 z = Complement[List @@ e2, {y}][[1]];

 nextV = Max[VertexList[g]] + 1;
 w = nextV;

 (* 生成新拓扑 *)
 newActiveEdges = {x <-> z, x <-> w, w <-> z};
 inertEdges = {x -> y, y -> z};

 Graph[VertexList[g] ~Join~ {w},
```

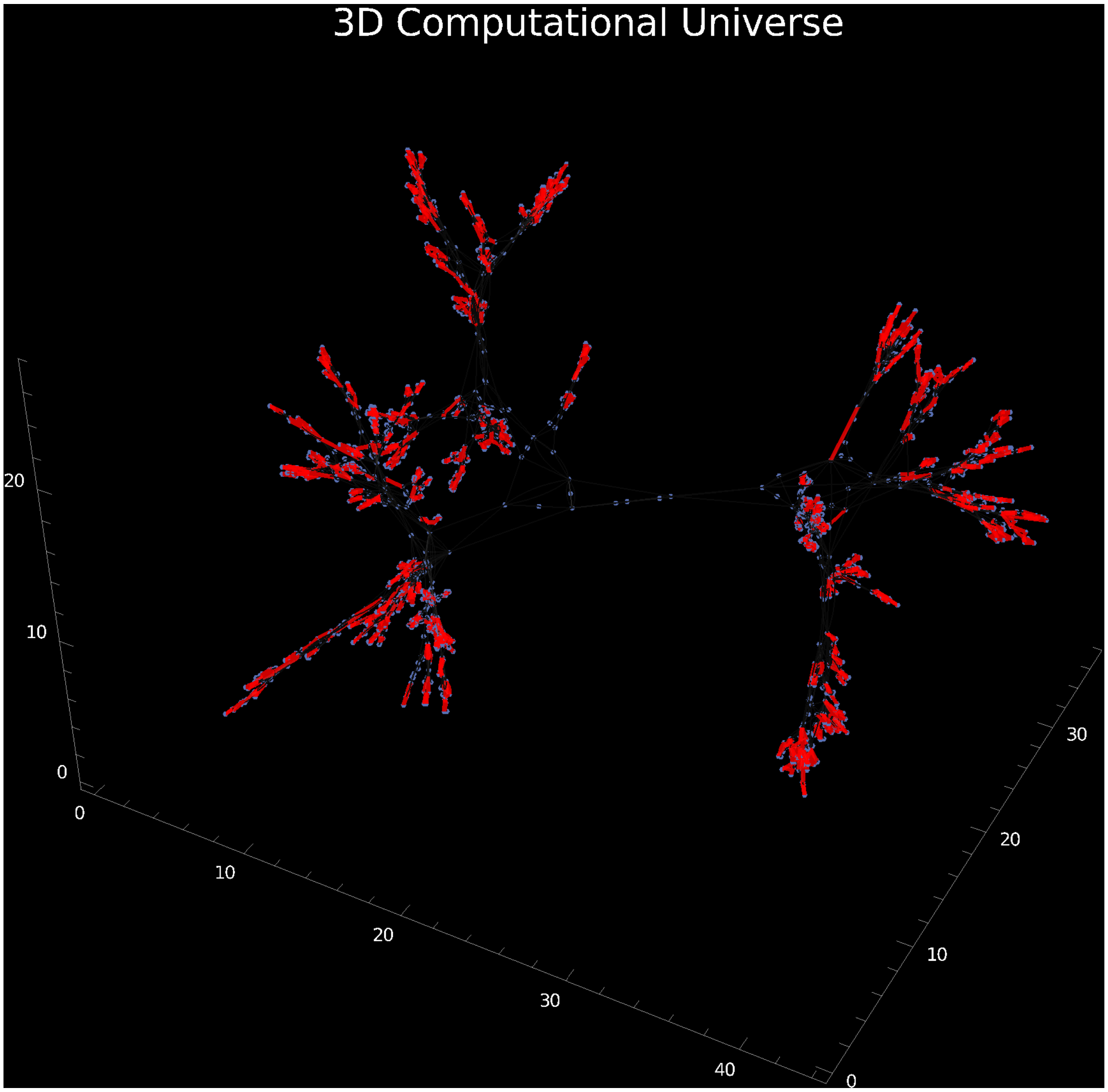
```
  Union[Complement[allEdges, {e1, e2}], newActiveEdges, inertEdges]]
];


(* ======================================== *)
(* PART 2: 3D 种子与模拟 *)
(* ======================================== *)

(* 关键：使用正四面体 (Tetrahedron) 作为种子 *)
(* 这迫使拓扑结构一开始就必须占据 3D 空间 *)
initG3D = CompleteGraph[3];


(* 步数：建议 1500-2000，太少看不出体积，太多计算慢 *)
steps = 2000;
Print["Building the 3D universe(Steps: ", steps, ")..."];

(* 运行模拟 *)
finalG = Nest[rcc3DStep, initG3D, steps];
Print["Simulation completed. Number of nodes:", VertexCount[finalG]];

(* ======================================== *)
(* PART 3: 强制 3D 可视化 (修复错误) *)
(* ======================================== *)

Print[];

(* 直接在 Graph3D 内部调用布局，不手动计算坐标 *)
Graph3D[finalG,

 (* 关键修复：直接告诉 Graph3D 使用弹簧电荷模型 *)
 (* Graph3D 环境会自动将其扩展为三维 *)
 GraphLayout → ,

 (* 视觉样式 *)
 VertexSize → 0, (* 隐藏节点，只看结构 *)
 EdgeStyle → {
  _UndirectedEdge → Directive[Opacity[0.8], Red, Thickness[0.003]], (* 活性：红 *)
  _DirectedEdge → Directive[Opacity[0.05], LightGray]       (* 历史：灰 *)
```

```
},

(* 环境设置 *)
Background → Black,
Boxed → True,    (* 开启边框！这能让你立刻判断是不是平的 *)
Axes → True,    (* 开启坐标轴，辅助观察深度 *)
AxesStyle → White,
ImageSize → Large,
PlotLabel → Style[, White, 20]
]
Print["We are delving into the depth of time and
    space, reconstructing the landscape of gravitational wells..."];

Module[{g = SimpleGraph[UndirectedGraph[finalG]],
 coords, curvatures, centerNode, dists, wellData, plot},

 (* 1. 计算核心指标：曲率(C) 与 距离(R) *)
 centerNode = First[SortBy[VertexList[g], -VertexDegree[g, #] &]];
 curvatures = LocalClusteringCoefficient[g];
 dists = GraphDistance[g, centerNode];

 (* 2. 构建 3D 引力井模型数据 *)
 (* X, Y 为 2D 布局坐标，Z 轴为曲率(代表引力深度) *)
 coords = GraphEmbedding[g, "SpringElectricalEmbedding"];

 wellData = Table[
  {coords[[i, 1]], coords[[i, 2]], -curvatures[[i]]}, (* 取负值模拟井的深度 *)
  {i, 1, VertexCount[g]}
 ];

 (* 3. 报告探测数据 *)
 Print["================================"];
 Print["REPORT"];
 Print["================================"];
 Print["井底深度 (Max Curvature): ", Max[curvatures]];
 Print["井缘坡度 (Avg Curvature Gradient): ", Mean[curvatures]];
 Print["================================"];

 (* 4. 3D 可视化渲染 *)
 Print["Rendering the 3D distribution map of the gravitational field..."];
```

```
 ListPlot3D[wellData,
  PlotStyle → Directive[Opacity[0.8], Specularity[White, 50]],
  ColorFunction → "DeepSeaColors",
  Mesh → None,
  AxesLabel → {"X", "Y", "Gravity Potential (Curvature)"},
  PlotLabel → Style["Gravitational Well of Computational Universe", 16, Bold],
  ViewPoint → {1.5, -2.5, 1.5},
  Boxed → False,
  ImageSize → Large
 ]
]
(* ========================================= *)
(* PART 4: 统计分析 (修正版) - 寻找“长尾” *)
(* ========================================= *)

Print[];

(* 【关键修复】：先强制转换为无向图，再简化，消除混合图错误 *)
simpleG = SimpleGraph[UndirectedGraph[finalG]];
degrees = VertexDegree[simpleG];

(* 2. 计算基本统计量 *)
maxDegree = Max[degrees];
meanDegree = N[Mean[degrees]];
Print["最大度 (Max Degree): ", maxDegree];
Print["平均度 (Mean Degree): ", meanDegree];

(* 3. 构建对数-对数图 (Log-Log Plot) *)
degreeCounts = Tally[degrees];
degreeCountsSorted = SortBy[degreeCounts, First];

(* 4. 绘制分析仪表盘 *)
statsPlot = Grid[{{
 (* 图 1: 标准直方图 *)
 Histogram[degrees, 30, ,
  ChartStyle → Directive[EdgeForm[None], Orange],
  AxesLabel → {, },
  PlotLabel → Style[, 14, Bold],
  ImageSize → 400],
```

```
(* 图 2: 双对数图 - 验证长尾的关键 *)
ListLogLogPlot[degreeCountsSorted,
 PlotStyle → Directive[PointSize[0.015], Cyan],
 Frame → True,
 GridLines → Automatic,
 FrameLabel → {, },
 PlotLabel → Style[, 14, Bold],
 ImageSize → 400,
 Epilog → {
  (* 辅助线 *)
  dashedLine = Line[{{1, Max[degreeCounts[[All, 2]]]}, {Max[degrees], 1}}];
  {Dashed, White, Opacity[0.3], dashedLine}
 }]
},
{
(* 图 3: 聚类系数分布 (现在不会报错了) *)
Histogram[LocalClusteringCoefficient[simpleG], 20,
 ChartStyle → Directive[EdgeForm[None], Purple],
 AxesLabel → {, },
 PlotLabel → Style[, 14, Bold],
 ImageSize → 400],

(* 图 4: 文本摘要 *)
Graphics[{
 Text[Style[StringForm[,
  VertexCount[simpleG], maxDegree, meanDegree],
  Left, White, 14]]
}, Background → Black, ImageSize → 400]
}
}, Spacings → {2, 2}, Background → Black];

(* 输出结果 *)
Print[];
statsPlot
```

```
Building the 3D universe(Steps: 2000)...
Simulation completed. Number of nodes:2003
Rendering 3D structure...
```



We are delving into the depth of time and
  space, reconstructing the landscape of gravitational wells...

================================

REPORT

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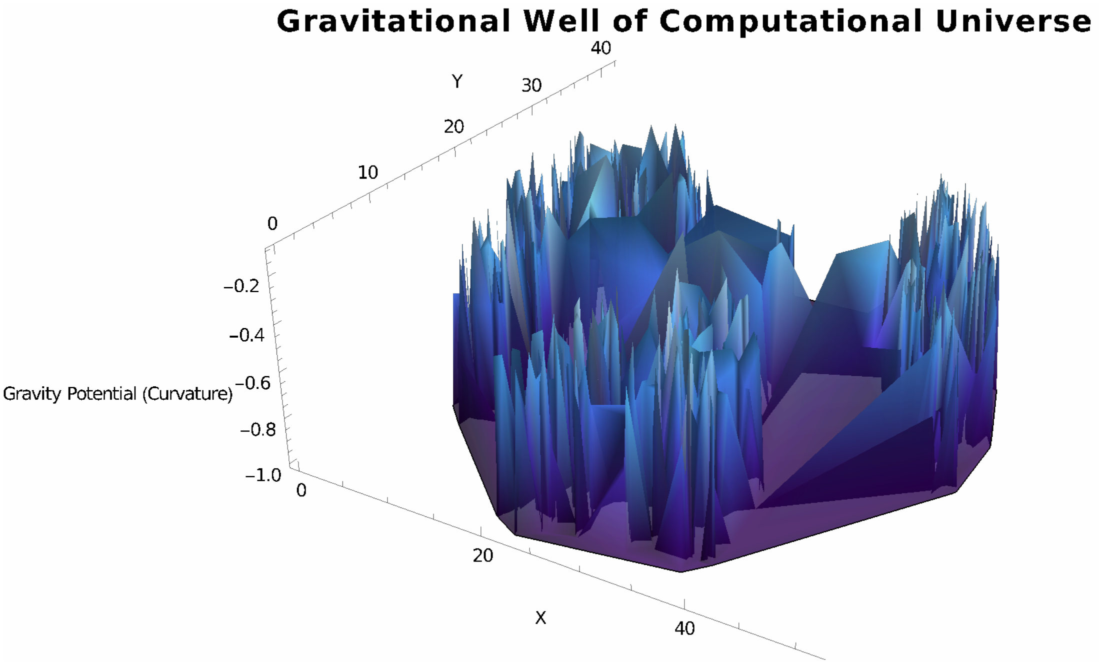
井底深度 (Max Curvature): 1

井缘坡度 (Avg Curvature Gradient): $\frac{52\,678\,350\,285\,653}{80\,433\,903\,349\,800}$

================================

Rendering the 3D distribution map of the gravitational field...

Out[194]=




```
Topological statistical analysis is in progress...
最大度 (Max Degree): 28
平均度 (Mean Degree): 4.86171
Analysis completed. Please check the Log-Log graph in the upper right corner.
```