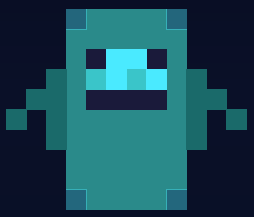


ARKE

GUARDIANS OF EARTH

A Pore-Scale Microbial Adventure
Based on Real Science from CompLaB3D

INSTRUCTION BOOKLET

CompLaB3D • University of Georgia • Pore-Scale Reactive Transport

CompLaB3D

Pore-Scale Reactive Transport Lab

ARKE: Guardians of Earth is an educational tile-based game that teaches biogeochemical concepts through interactive microbial gameplay.

Based on research from the **University of Georgia**

CompLaB3D Pore-Scale Reactive Transport Framework

Game Engine: Godot 4.2+

Genre: Educational / Strategy / Tile-based

Players: 1

Platform: PC / Web (itch.io)

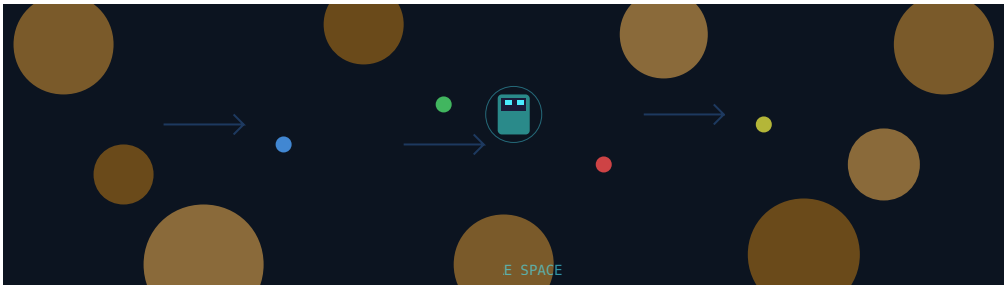
All game art, music, and sound effects are procedurally generated.
No external assets required.

This instruction booklet contains important information about gameplay mechanics, characters, worlds, and the real science behind the g

Please read it thoroughly before beginning your mission.

SECTION 1

THE STORY



Deep beneath the surface of the Earth, between grains of rock and soil, there exists a hidden world. I the microscopic spaces called **pores**, water flows carrying dissolved chemicals—the fuel of life itself.

For billions of years, tiny organisms called **archaea** have lived here in the dark, feeding on chemicals that seep up from deep underground. They are Earth's invisible guardians—consuming **methane (CH** a greenhouse gas **80 times** more potent than CO_2, and **nitrate (NO_3^-)**, which would otherwise beco **nitrous oxide (N_2O)**, a gas **300 times** more potent than CO_2.

Without these microbes, Earth's climate would spiral out of control.

YOUR MISSION

You are **ARKE**—a young methanotrophic archaeon, newly awakened in the pore space. Guided b the ancient **Elder Archaeon Prime**, you must navigate through five increasingly hostile environments:

1. Eat **substrates** (dissolved chemicals) to survive and grow
2. Manage your **Health**, **Energy**, and **Growth**
3. Place **biofilm colonies** to secure territory and protect the planet
4. Outcompete **rival microbes** who hunt for the same food
5. Survive **toxic zones**, starvation, and hostile environments

THE AWAKENING

Elder Archaeon Prime:

"Wake up, young one. You're deep in the subsurface now, between the grains. This is your home—th pore space."

ARKE:

"Where... where am I? Everything is so dark..."

Elder:

"Look around you. See those brown walls? Those are rock grains. The dark blue space between ther is water—your world. And those glowing particles? That's your food."

Elder:

"There's methane rising from below—CH_4. It's a greenhouse gas, 80 times more potent than CO_2. And nitrous oxide seeping from thawing soil above—300 times more potent! If these gases reach the atmosphere... the planet warms."

ARKE:

"What can I do? I'm just one microbe..."

Elder:

"One microbe can become billions. Eat substrates, grow your biomass, and when you're ready—divide! Place biofilm colonies across the pore space. Each colony is a sentinel, consuming greenhou gases. You are Earth's climate shield. Now go, young one. The Soil Frontier awaits."

OBJECT OF THE GAME

Navigate through **10 levels** across **5 unique environments**, each inspired by real subsurface ecosystems. In each level, you must place a target number of **biofilm colonies** by eating substrates growing your biomass to the division threshold.

To Win Each Level:

- Eat substrates to fill your Growth bar
- Press **SPACE** when Growth reaches 100 to divide
- Place the required number of colonies

You Lose If:

- Your Health drops to 0 (starvation)
- Toxic zones drain your Health too fast
- Rivals consume all available food

- Advance to the next level
- (You can always retry the level!)

REMEMBER

Every molecule of methane (CH_4) you eat prevents greenhouse warming. Every nitrate (NO_3^-) you consume prevents nitrous oxide release. **You are playing for the planet!**

SECTION 2

CHARACTERS

ARKE

A young **methanotrophic archaeon**—a single-celled organism that feeds on dissolved chemicals in underground water. ARKE is Earth's front-line defender against greenhouse gas emissions, capable of consuming methane and other substrates to grow biomass an reproduce through binary fission (division).

`TYPE: Player Character • SIZE: 32×32px • SPEED: 2.5 tiles/sec`

ARKE Directional Sprites

UP DOWN LEFT RIGHT EATING DIVIDE!

ARKE'S VITAL STATS

HP

Health — Drains at 1.5/sec (starvation). Restored by eating. Death at 0.

EN

Energy — Drains at 0.8/sec. Powers planktonic flow-riding (SHIFT). Restored by eating.

GR

Growth — Does NOT decay! Accumulates as you eat. Press SPACE to divide at 100.

ELDER ARCHAEON PRIME

ELDER ARCHAEON PRIME

An ancient archaeon who has guarded the subsurface for eons. The Elder serves as you mentor, providing mission briefings before each level and teaching you the science behin your abilities. Appears during cutscenes and narrative sequences.

`TYPE: Mentor / NPC • APPEARS: Cutscenes & Briefings`

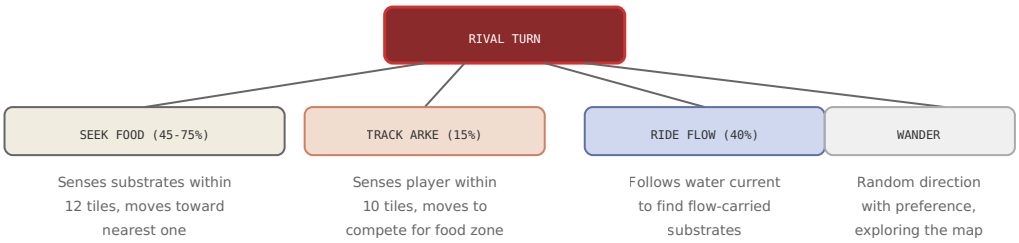
RIVAL MICROBES

RIVAL MICROBE

Competing bacteria that hunt for the same substrates as you. Rivals are **invulnerable**— you cannot kill or damage them. They don't attack you directly, but they consume food aggressively, creating deadly scarcity. The more rivals in a level, the harder it becomes to survive.

`TYPE: Enemy (Competitor) • SIZE: 10×10px • SPEED: 2.5 tiles/sec • SENSE: 12 tiles`

Rival Decision Tree



BIOFILM COLONIES

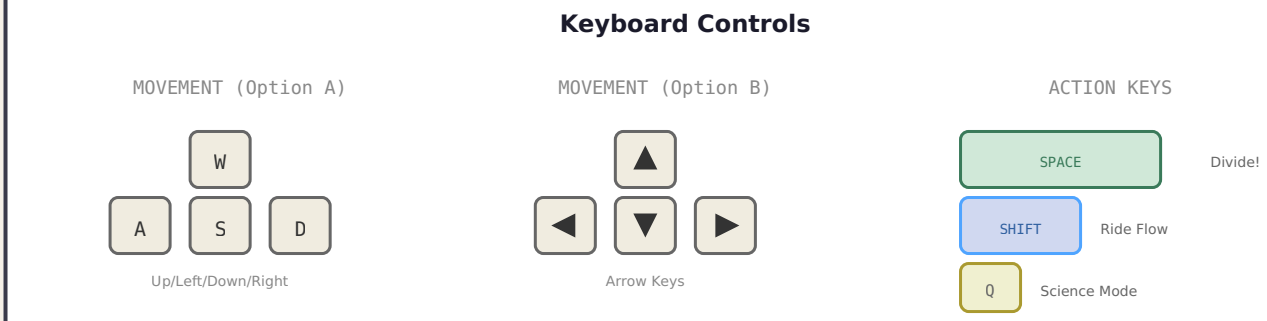
BIOFILM COLONY

When ARKE divides, a permanent biofilm colony is placed on the map. Colonies are stationary sentinels that **passively consume** nearby substrates (within 1.5 tiles). They cannot be destroyed. Each colony placed earns **+100 points** and counts toward the level goal.

`TYPE: Stationary Ally • SIZE: 12×12px • FEED RANGE: 1.5 tiles • PERMANENT`

SECTION 3

CONTROLS & MOVEMENT



System Keys

Key	Function
ESC / P	Pause game — opens pause menu (Resume / Mute / Quit)
M	Toggle sound on/off (mute all audio)
ENTER	Advance dialogue, confirm menu selection, start level

HOW ARKE MOVES

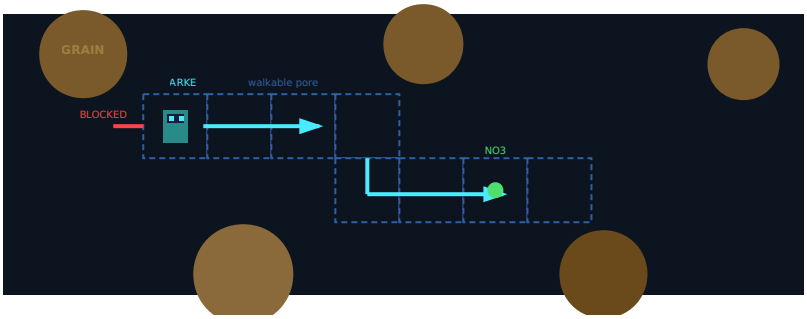
Normal Movement

- **Speed:** 2.5 tiles per second
- **Direction:** 4-directional (no diagonals)
- Move through **pore space** (dark blue tiles)
- Cannot pass through **grains** (brown tiles)
- Can walk through your own **colonies**
- Smooth animation between tiles

Planktonic Mode (SHIFT)

- **Speed:** 5.0 tiles per second (2×!)
- Hold SHIFT on tiles with **water flow**
- Automatically follow flow direction
- **Costs:** 0.5 Energy per move
- Blue glow shows when active
- Essential for fast-flow levels!

Movement Through Pore Space



ARKE navigates tile-by-tile through pore space. Grains block movement. Substrates are consumed on contact.

PLANKTONIC FLOW-RIDING

How Flow Riding Works

Energy Cost: -0.5 EN per move

Hold SHIFT to activate on flow tiles

FLOW RIDING TIPS

- Flow moves from **INLET** (left, blue) to **OUTLET** (right, green)
- Not all tiles have flow—check the **Science Mode (Q)** overlay to see flow directions
- Flow speed varies: some channels are **FAST FLOW** (2.5× speed bonus)
- Essential in Chapters 4-5 where substrates move very quickly
- Watch your Energy bar! Running out strands you at normal speed

TILE TYPES YOU'LL ENCOUNTER

PORE
Walkable water

GRAIN
Impassable rock

BIOFILM
Your colonies

TOXIC
-20 HP/sec!

FAST FLOW
2.5× speed

INLET
Water enters

OUTLET
Water exits

VOID
Map boundary

EATING IS AUTOMATIC

You don't need to press a button to eat! Simply **move over a substrate particle** and ARKE will consume it automatically. You'll hear a chiptune sound effect and see your HP, EN, and GR bars update instantly.

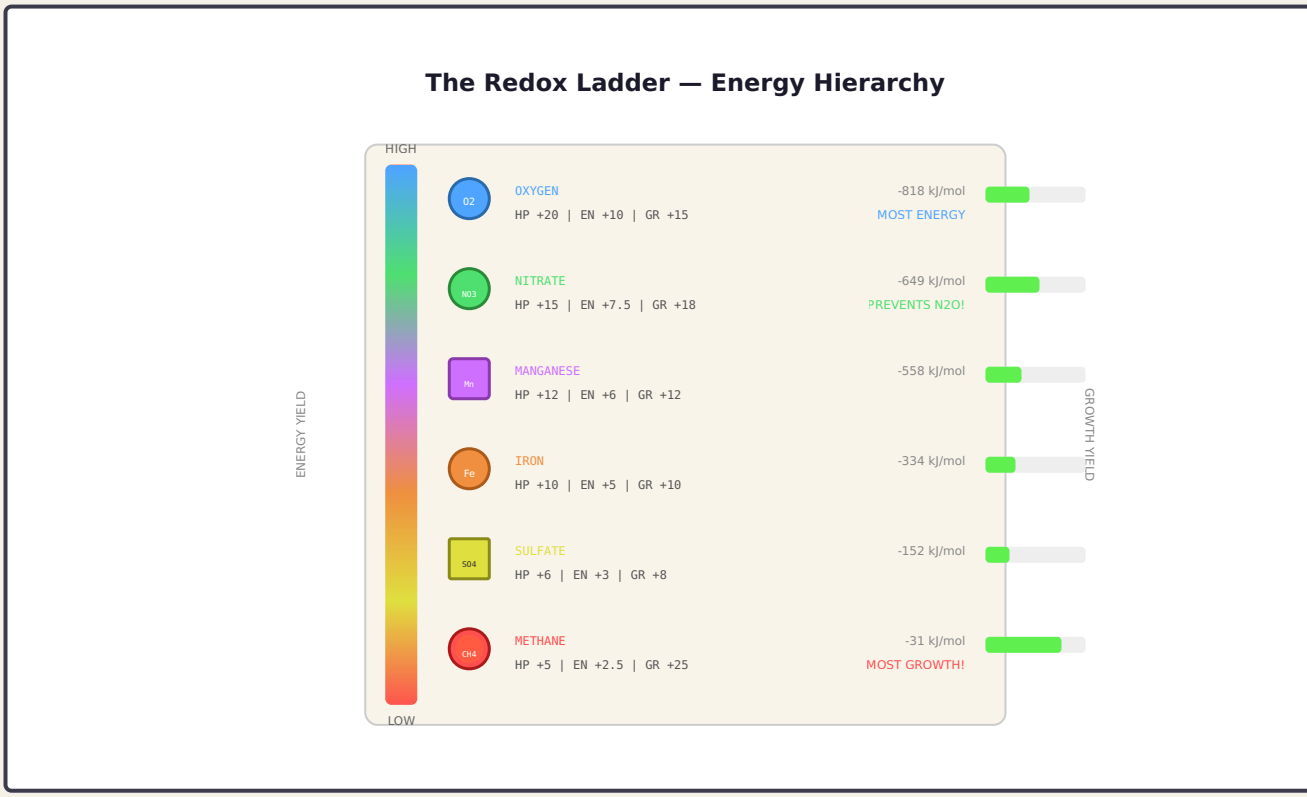
SECTION 4

SUBSTRATES — YOUR FOOD

Substrates are dissolved chemicals carried by water flow through the pore space. They are your food energy, and building material. Each substrate provides different amounts of **Health**, **Energy**, and **Growth**.

THE REDOX LADDER (Real Science!)

In real microbiology, organisms use chemicals in a specific thermodynamic order called the **Redox Ladder**. Oxygen provides the most energy; methane provides the least. The game faithfully represents this hierarchy



SUBSTRATE DETAILS

O2 — OXYGEN

Aerobic respiration. Highest energy yield in nature. Available in surface soils and thawing permafrost.

+20 HP | +10 EN | +15 GR | +10 PTS
Levels: 1, 2, 7

NO3 — NITRATE

Denitrification. Prevents N_2O (300× CO_2) fro forming. Best all-around substrate.

+15 HP | +7.5 EN | +18 GR | +25 PTS
Levels: 1-4, 7-10 | CLIMATE BONUS!

Mn(IV) — MANGANESE

Manganese reduction. Angular purple particles. Mid-range energy and growth.

+12 HP | +6 EN | +12 GR | +10 PTS
Levels: 4, 9, 10

Fe(III) — IRON

Iron reduction. Moderate energy and growth Found in deep sediments and vents.

+10 HP | +5 EN | +10 GR | +10 PTS
Levels: 3, 4, 6, 9, 10

SO4 — SULFATE

Sulfate reduction. Produces H_2S (toxic zones!). Low energy but necessary in anaerobic zones.

+6 HP | +3 EN | +8 GR | +10 PTS
Levels: 5-10

CH4 — METHANE

Methanotrophy! Lowest energy but **HIGHES GROWTH**. Prevents greenhouse warming (80× CO_2). Your signature food!

+5 HP | +2.5 EN | +25 GR | +35 PTS
ALL LEVELS | CLIMATE BONUS!

FEEDING STRATEGY

When Health is high (>50): Prioritize CH_4 for maximum growth (fastest path to division).

When Health is moderate (30-50): Eat NO_3 for balanced recovery.

When Health is critical (<30): Eat O_2 or NO_3 immediately—survival first!

Remember: Substrates spawn near the INLET and drift with the flow.

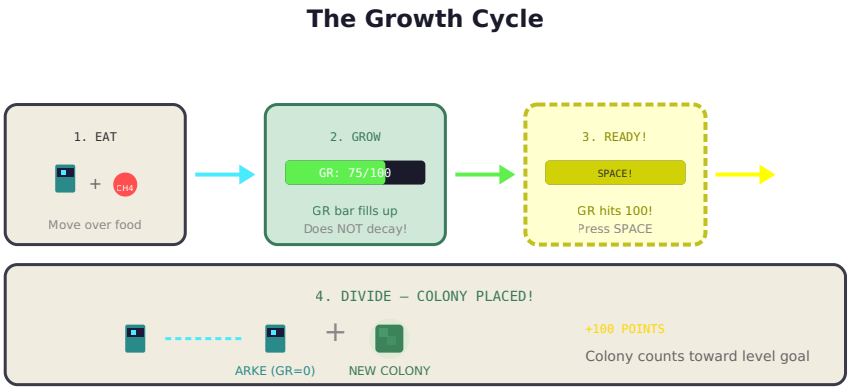
HOW SUBSTRATES APPEAR

New substrates spawn every **1.2 seconds** near the INLET (left side). They drift with the water flow, moving righ across the map. Each level has a **spawn density** (2-6 per cycle) that determines food abundance. Substrates limited lifetimes—if nobody eats them, they eventually disappear.

SECTION 5

GROWTH & DIVISION

Growth is the core mechanic of ARKE. Every substrate you eat adds to your Growth bar (GR). When reaches **100**, you can **divide**—placing a permanent biofilm colony on the map. This is how you win e level!



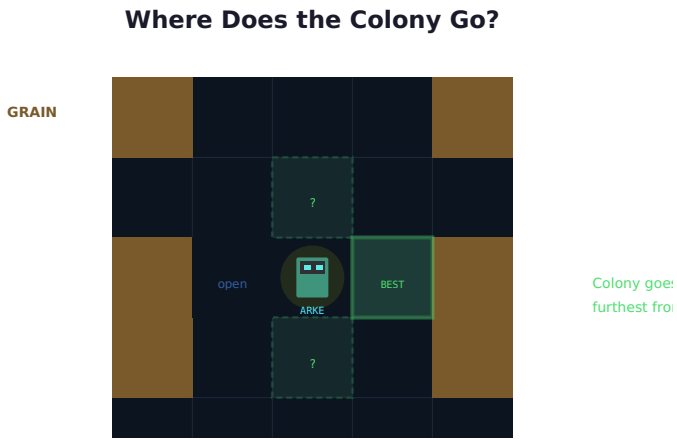
SUBSTRATES NEEDED TO DIVIDE

Substrate	Growth/Eat	Eats to Divide	Efficiency Rating
CH4 (Methane)	+25 GR	**4 eats**	BEST for growth
NO3 (Nitrate)	+18 GR	6 eats	Great balanced option
O2 (Oxygen)	+15 GR	7 eats	Good energy, decent growth
Mn(IV)	+12 GR	9 eats	Mid-range
Fe(III) (Iron)	+10 GR	10 eats	Mid-range
SO4 (Sulfate)	+8 GR	13 eats	Slowest growth

PRO TIP

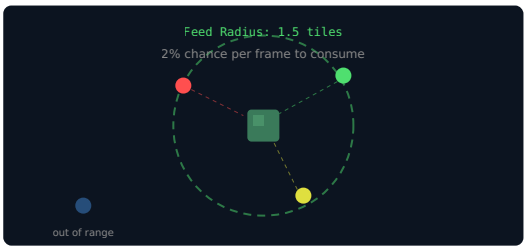
The fastest way to divide is to eat **4 methane particles (CH_4)**. But methane only gives +5 HP—if your healt is low, you'll die before you can divide! Mix in NO_3 or O_2 to keep your health up while building growth.

COLONY PLACEMENT MECHANICS



The game automatically selects the best adjacent pore tile — preferring open space far from grain walls.

COLONY PASSIVE FEEDING



LEVEL COMPLETION

EAT → GROW → DIVIDE → COLONY → REPEAT ×N

Level	Goal	Level	Goal
1. First Breath	**3** colonies	6. Vent Guardians	**8** colonies
2. Roots of Life	**5** colonies	7. Thawing Grounds	**6** colonies
3. Into the Depths	**4** colonies	8. The Great Thaw	**8** colonies
4. The Hungry Dark	**6** colonies	9. The Abyss	**8** colonies

5. The Methane Vents	**5** colonies	10. Earth's Last Stand	**12** colonies

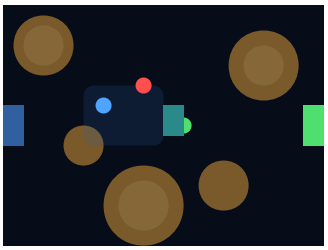
SCORING

+10 pts per substrate eaten • **+25 bonus** for CH_4 • **+15 bonus** for NO_3 • **+100 pts** per colony placed • **+1,000 pts** per level completed

SECTION 6

WORLDS & ENVIRONMENTS

ARKE's journey spans **5 unique environments** across **10 levels**, each inspired by real subsurface ecosystems studied by the CompLaB3D research team. Each environment has its own color palette, pore geometry, and challenges.

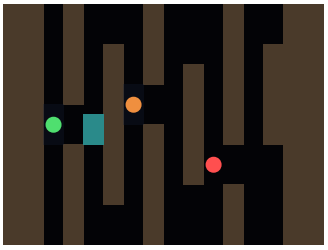


CHAPTER 1: THE SOIL FRONTIER

Levels 1-2 • Environment 0

Shallow soil with wide-open pore spaces between rounded rock grains. Water flows gently, carrying abundant nutrients including **oxygen**. The safest environment— perfect for learning the basics.

Palette: Brown grains, tan highlights, blue water
Geometry: Circular grains, ~65-70% porosity (lots of space)
Substrates: O_2, NO_3, CH_4
Hazards: None (Level 1) / 1 rival (Level 2)

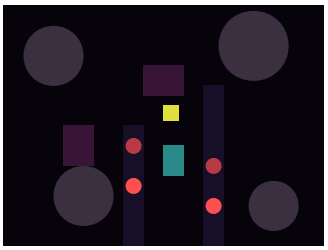


CHAPTER 2: THE DEEP SEDIMENT

Levels 3-4 • Environment 1

Deep beneath the ocean floor. No oxygen here! Narrow, maze-like corridors carved through compacted sediment. Flow is sluggish and food is scarce. **Navigation skill** becomes critical.

Palette: Very dark brown, nearly black water
Geometry: Recursive maze algorithm, ~45-50% porosity (tight!)
Substrates: NO_3, Fe(III), Mn(IV), CH_4 (no O_2!)
Hazards: 2-3 rivals, slow flow, tight corridors

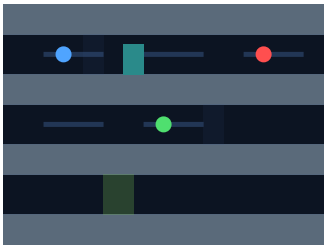


CHAPTER 3: THE METHANE SEEPS

Levels 5-6 • Environment 2

Methane bubbles up through vertical vent channels. **Toxic H_2S zones** appear for the first time! Purple-tinted world with abundant CH_4 but dangerous terrain. This is where ARKE truly becomes Earth's climate shield.

Palette: Dark purple grains, violet water, magenta toxins
Geometry: Soil + vertical vent channels, ~55-60% porosity
Substrates: SO_4, CH_4, Fe(III)
Hazards: 15-20% toxic zones, 2-3 rivals

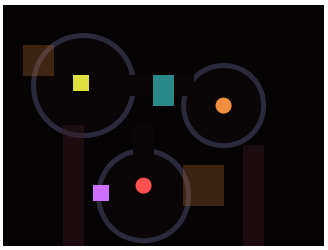


CHAPTER 4: THE PERMAFROST EDGE

Levels 7-8 • Environment 3

Thawing permafrost releases ancient carbon. **Fast horizontal flow channels** between ice layers demand mastery of **SHIFT (flow riding)**. Substrates race past at high speed. Oxygen returns briefly in Level 7!

Palette: Gray-blue grains, icy blue water, green toxins
Geometry: Horizontal layers + vertical connectors, ~50-55% porosity
Substrates: O_2 (Lv7), NO_3, SO_4, CH_4
Hazards: 10-15% toxic zones, 3-4 rivals, fast flow (0.8-1.0×)



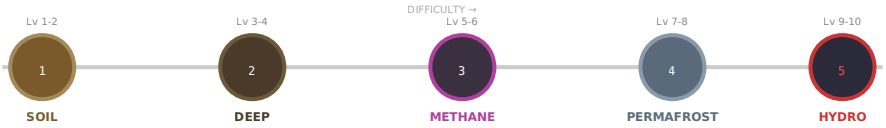
CHAPTER 5: THE HYDROTHERMAL REALM

Levels 9-10 • Environment 4

The deepest, most extreme environment. Chaotic chamber-and-tunnel geolog near hydrothermal vents. **Maximum toxic coverage (25%)**, extreme flow speeds, and **5 rivals**. The full redox ladder (minus O_2) is available. **This is th final challenge.**

Palette: Nearly black grains, dark red water, orange heat toxins
Geometry: Circular chambers + random tunnels + vent columns
Substrates: SO_4, Fe(III), Mn(IV), CH_4, NO_3 (Lv10)
Hazards: 20-25% toxic, 4-5 rivals, extreme flow (1.2-1.5×)

JOURNEY OVERVIEW

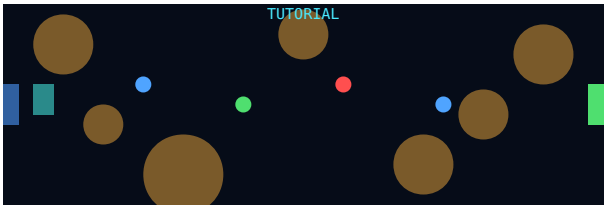


SECTION 7

LEVEL GUIDE

LEVEL 1: FIRST BREATH

Chapter 1 — The Soil Front



GOAL	MAP	RIVALS	TOXIC
3 colonies	30×20	0	None

Strategy: Pure tutorial. No enemies, no hazards. Learn to move (WASD/Arrows), eat substrates (auto on contact), watch your Growth bar fill, and press SPACE to divide. Wide open pores with 70% porosity. Take your time.

LEVEL 2: ROOTS OF LIFE

Chapter 1 — The Soil Front

GOAL	MAP	RIVALS	TOXIC
5 colonies	35×22	1	None

Strategy: Your first rival appears! It wanders seeking food. Move quickly to eat substrates before it does. Larger map requires navigation. Try using SHIFT on flow tiles to outpace the rival. Still O_2-rich.

LEVEL 3: INTO THE DEPTHS

GOAL	MAP	RIVALS	TOXIC
4 colonies	**35×25**	**2**	**None**

> **Strategy:** No oxygen! Tight maze corridors (50% porosity). Slow flow (0.3×). Food is scarce (density 3). NO_3 is your best friend (+15 HP, +18 GR). Two rivals compete. Navigate carefully—dead ends waste time

LEVEL 4: THE HUNGRY DARK

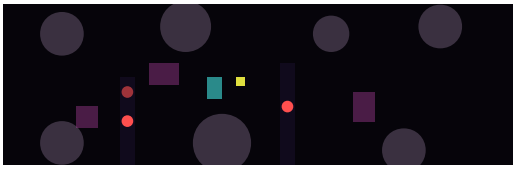
Chapter 2 — The Deep Sedime

GOAL	MAP	RIVALS	FLOW
6 colonies	40×28	3	0.25× (crawl)

Strategy: Survival test. Very scarce food (density 2), tightest porosity (45%), three rivals. Manganese (Mn^{IV}, purple) appears. Must be extremely efficient with every substrate. Eat CH_4 for growth when safe, NO_3/Fe when desperate.

LEVEL 5: THE METHANE VENTS

Chapter 3 — The Methane See



GOAL	MAP	RIVALS	TOXIC
5 colonies	35×22	2	15%

Strategy: Toxic zones appear! Only SO_4 and CH_4 available. Abundant food (density 5) compensates. Check minimap for purple dots (toxic). Avoid or cross quickly (−20 HP/sec!). CH_4 = primary growth source. Sulfate for energy maintenance.

LEVEL 6: VENT GUARDIANS

Chapter 3 — The Methane See

GOAL	MAP	RIVALS	TOXIC
8 colonies	40×25	3	20%

Strategy: 8 colonies needed (double Level 5). Fe(III) now available for better energy (+10). Toxic zones cover 1 in 5 tiles. Three rivals. Balance avoiding toxins while maintaining food access. Plan colony locations near rich food zones.

LEVEL 7: THAWING GROUNDS

Chapter 4 — The Permafrost Ed

GOAL	MAP	RIVALS	FLOW
6 colonies	**40×25**	**3**	**0.8× (fast!)**

> **Strategy:** Oxygen returns! Fast flow (0.8×) makes SHIFT essential. Abundant food (density 6). O_2 provides strongest HP recovery (+20). Use flow riding to cover distance and intercept fast-moving substrates. Only 10% toxic—manageable.

LEVEL 8: THE GREAT THAW

Chapter 4 — The Permafrost Ed

GOAL	MAP	RIVALS	FLOW
8 colonies	45×28	4	1.0× (very fast!)

Strategy: No oxygen again—thaw accelerates. Fastest flow yet (1.0×). Largest map so far. Four rivals! Must ride flow constantly with SHIFT. NO_3 is critical (+15 HP, +18 GR). Very difficult—requires expert navigation.

LEVEL 9: THE ABYSS

Chapter 5 — The Hydrothermal Rea

GOAL	MAP	RIVALS	TOXIC
8 colonies	45×25	4	20%

Strategy: Deep-sea vents. Full redox ladder (minus O_2). Extreme flow (1.2×). Toxic everywhere (20%). Scarce food (density 4). Four rivals. Chamber-based topology. Master all mechanics. Requires expert planktonic riding and efficient foraging.

LEVEL 10: EARTH'S LAST STAND

FINAL LEVE

GOAL	MAP	RIVALS	TOXIC
12 colonies!	50×30	5 (MAX)	25% (MAX)

THE ULTIMATE TEST. Everything at maximum. Largest map (50×30 = 1,500 tiles). Most colonies needed (12). Fastest flow (1.5×). Most toxic (1 in 4 tiles!). Most rivals (5). All substrates available except O_2. Victory requires complete mastery of all mechanics. **Completing this level triggers the VICTORY screen showing your total score and climate impact!**

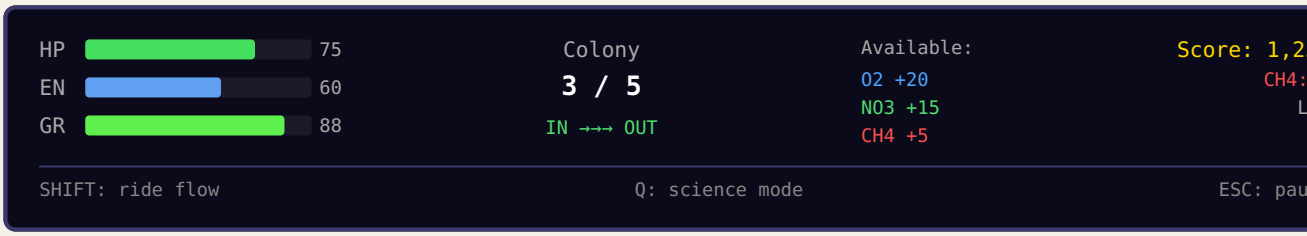
GAME OVER

If your Health reaches 0, you die. Don't panic! Press **ENTER** after 2 seconds to retry the same level. Your score for that level resets, but you keep your global progress.

SECTION 8

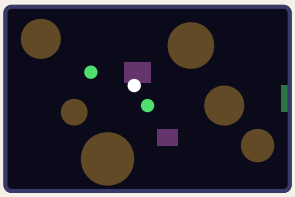
THE HUD & INTERFACE

The Heads-Up Display (HUD) shows everything you need to survive. Learn to read it at a glance!



Element	Location	What It Shows
HP Bar	Bottom-left	Health. Green >60, Yellow 35-60, Orange 15-35, Red <15 (flashing!)
EN Bar	Bottom-left	Energy for flow riding. Drains at 0.8/sec.
GR Bar	Bottom-left	Growth toward division. Flashes yellow when full (SPACE!)
Colony X/Y	Center-left	Current colonies placed / goal needed to win
Flow Compass	Center	IN → OUT shows flow direction; TOXIC warning if present
Redox List	Center-right	Available substrates and their energy values
Score	Top-right	Accumulated points this level
CH4 Count	Right	Methane consumed (climate impact tracker)
Level #	Right	Current level number

THE MINIMAP



The minimap appears in the **top-right corner** during gameplay. It shows:

- **Brown** = Rock grains (impassable)
- **Purple** = Toxic zones (danger!)
- **Green dots** = Your colonies
- **White dot** = ARKE (you, blinking)
- **Green edge** = Outlet

Use the minimap to plan routes, avoid toxic zones, and find open pore space for colonies.

SCIENCE MODE (PRESS Q)

SCIENCE OVERLAY

Press **Q** to toggle the science overlay. It shows:

- **Flow direction arrows** on every tile with water current

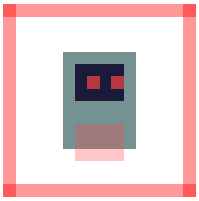
- **Heat map**: Blue (slow) → Cyan → Green → Yellow (fast)
- **Speed labels** showing numeric flow values
- **Tile type labels** (PORE, FAST, TOXIC, INLET, etc.)

Use this to plan flow-riding routes and understand substrate delivery patterns!

SECTION 9

HAZARDS & DANGERS

BEWARE! THE FOLLOWING ARE DEADLY:



STARVATION

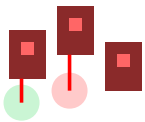
Your Health drains at **1.5 HP per second**, always. If you stop eating, you die in about 67 seconds. Screen edges flash red when HP drops below 30. **"STARVING!"** text appears a a warning.

`DAMAGE: -1.5 HP/sec (constant) • SCREEN: Red flash when HP < 30`

TOXIC ZONES (H_2S)

Purple/magenta tiles that deal **20 HP per second** while standing on them. Combined wit starvation, that's **21.5 HP/sec total**! Visible on the minimap as purple dots. Cross quickly or find alternate routes.

`DAMAGE: -20 HP/sec • LEVELS: 5-10 • COVERAGE: 10-25%`



FOOD COMPETITION (RIVALS)

Rivals consume substrates **instantly on contact**, just like you. They can't be killed or stopped. They sense food from 12 tiles away and become more aggressive when hungry More rivals = less food = faster starvation.

`INDIRECT KILL • RIVALS: 0-5 per level • INVULNERABLE`

DEAD-END PORES

Some corridors lead nowhere! If you wander into a dead end, you waste precious time backtracking while starvation continues. **Use the minimap and Science Mode (Q)** to identify dead ends before entering. Tiles with no flow arrows are likely dead ends.

SECTION 10

TIPS & STRATEGIES

SURVIVAL TIPS

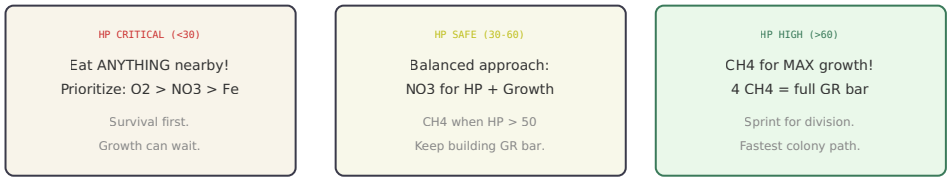
Early Game (Levels 1-4)

- Learn the controls in Level 1 with no pressure
- Always keep HP above 50 as a safety margin
- Eat O_2 when available—it's the best energy source
- Mix CH_4 (growth) with NO_3 (balanced)
- Follow the flow arrows to find substrate-rich zones
- Use the minimap to plan your route

Late Game (Levels 5-10)

- Master SHIFT (flow riding)—it's essential!
- Check minimap for toxic zones BEFORE moving
- Use Science Mode (Q) to see flow patterns
- Race rivals to substrate spawn points near INLET
- Place colonies strategically near food-rich areas
- Cross toxic zones only when HP is high (>70)

THE ART OF EFFICIENT EATING



SCORING GUIDE

Action	Points	Notes
Eat any substrate	+10	Base score for all types
Eat CH_4 (methane)	+35	+10 base +25 climate bonus
Eat NO_3 (nitrate)	+25	+10 base +15 climate bonus
Place colony	+100	Each division
Complete level	+1,000	Reach colony goal

MAXIMIZE YOUR SCORE

CH_4 gives the most points per eat (35 pts) AND the most growth (+25 GR). Eating 4 methane to divide gives 140 pts from eating + 100 pts from colony = **240 pts per division cycle**. That's the fastest score per cycle in the game!

SECTION 11

THE SCIENCE BEHIND ARKE

REAL SCIENCE, REAL IMPACT

Every mechanic in ARKE is based on real biogeochemistry studied by the CompLaB3D research team at the University of Georgia. Here are the science facts you unlock after completing each level:

LEVEL 1: THE REDOX LADDER

Microbes use chemicals in a strict thermodynamic order: O_2 → NO_3 → Mn(IV) → Fe(III) → SO_4 → CH_4. Each step yields less energy. This "redox ladder" governs all subsurface life.

LEVEL 2: METHANOTROPHY

Methanotrophic archaea like ARKE consume methane (CH_4) before it reaches the atmosphere. They prevent ~90% of ocean methane from escaping. Without them, Earth would be 3-5°C warmer.

LEVEL 3: DENITRIFICATION

Denitrifying microbes convert NO_3→N_2 (harmless gas). Without them, nitrate becomes N_2O (nitrous oxide), a greenhouse gas 300× more potent than CO_2 that also destroys the ozone layer.

LEVEL 4: DIFFUSION vs ADVECTION

The Péclet number (Pe) determines whether chemicals move by diffusion (random molecular motion) or advection (bulk water flow). In tight pores, diffusion dominates. In wide channels, flow carries everything.

LEVEL 5: MONOD KINETICS

Growth rate = μ_{max} × S/(K_s+S). When substrate S is abundant, growth is maximum. When S is scarce, growth slows. The half-saturation constant K_s determines how efficiently a microbe captures food.

LEVEL 6: BIOFILM FORMATION

Biofilms are communities of microbes embedded in a protective matrix. CompLaB3D models biofilm spreading using Cellular Automata (CA): when local biomass exceeds a threshold, it spreads to adjacent cells—just like ARKE's colony placement!

LEVEL 7: ANAEROBIC METHANE OXIDATION

AOM (Anaerobic Oxidation of Methane) is performed by archaea + sulfate-reducing bacteria working together. They consume CH_4 using SO_4 as the oxidant, without needing any oxygen. A critical climate process.

LEVEL 8: PERMAFROST CARBON FEEDBACK

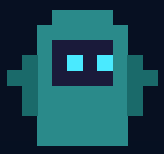
Arctic permafrost stores ~1,500 gigatons of carbon. As it thaws, microbes decompose this ancient organic matter, releasing CH_4 and CO_2. Methanotrophs are the last line of defense against this carbon escaping.

LEVEL 9: HYDROTHERMAL CHEMISTRY

At ocean-floor hydrothermal vents, superheated water carries dissolved metals (Fe, Mn) and gases (H_2S, CH_4). Chemosynthetic microbes thrive here without sunlight—powered entirely by redox chemistry.

LEVEL 10: YOU ARE EARTH'S CLIMATE SHIELD

Earth's subsurface contains more microbial biomass than all surface life combined. These invisible organisms regulate o atmosphere, filter our water, and cycle nutrients. You played as one of them—and now you understand their vital role.



"One microbe can become billions."

— Elder Archaeon Prime

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