Introduction to Electrical Circuits

Series, parallel, and series-parallel — the shape of every CP circuit.

LEARNING OBJECTIVES

What we'll know when we're done

1. **Recognize** series, parallel, and series-parallel circuit shapes when looking at any CP system.
2. **Predict** how each shape behaves — what stays common across elements and what splits.
3. **Reduce** a series-parallel CP circuit to a single equivalent resistance using a 5-step procedure.
4. **Read** CP circuit symptoms by shape — series-side IR drop versus parallel-side imbalance.
5. **Use** IR-drop math to predict voltage available at the anode array, given cable R and current.

THE HOOK

12 volts, 8 amps — and 6 amps gone since the last visit

THE SCENARIO

You're out on a routine bi-monthly check. Rectifier reads 12 V DC, 8 A — but two months ago, on the last visit, the same dial setting was putting **14 A**. Six amps have gone somewhere in the circuit.

At the junction box, voltage reads **11.1 V** — almost a full volt lost on the cable alone. And the six anodes in the groundbed aren't sharing current evenly — the inner two are carrying nearly twice the outer two.

RECTIFIER · TODAY

12.0 V

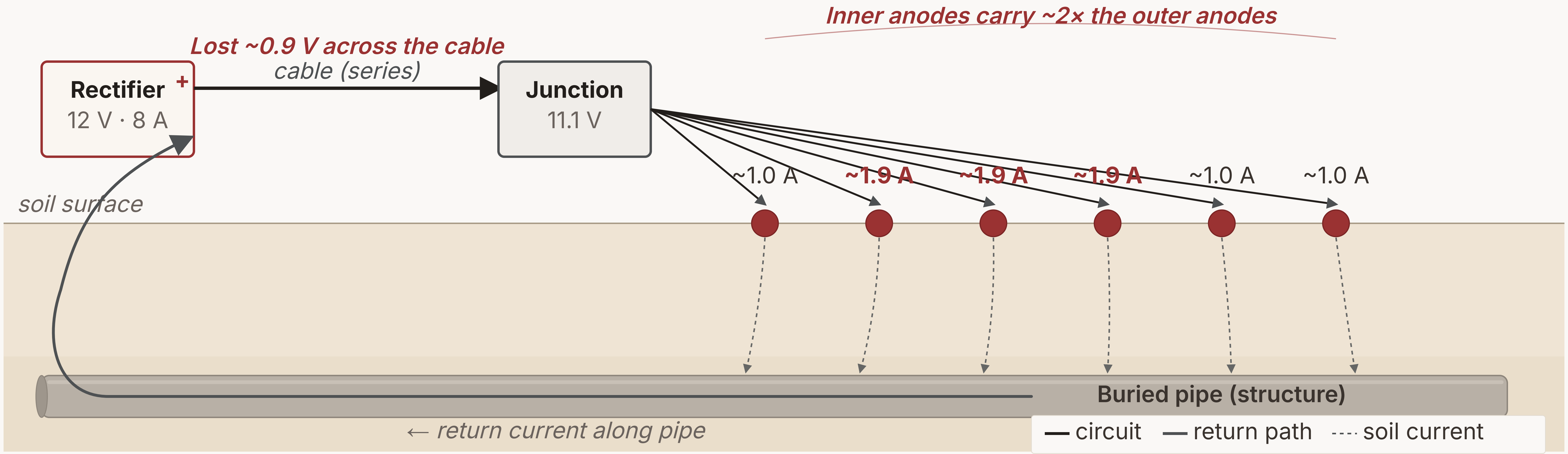
8.0 A

TWO MONTHS AGO: 14 A

This isn't a rectifier problem. It isn't a soil problem. It's a circuit problem.

THE HOOK · FIELD READINGS

Where the lost volts and uneven currents land



SERIES SIDE

Lost ~0.9 V across the cable on the way out

READ THE SHAPE

Series IR drop on one side, parallel imbalance on the other

PARALLEL SIDE

Branch resistances differ — current splits unevenly

It's not the rectifier.
It's not the soil.
It's a circuit.

Understanding why this is happening — and what to do about it — starts with knowing how the three shapes of DC circuits behave.

That's what this module is for.

REFERENCE

Three quantities, briefly

Volts · Amperes · Ohms

V

VOLTS

Voltage

Electrical pressure that drives current through the circuit.

I

AMPERES

Current

Rate of charge flow — what does the actual protecting in CP work.

R

OHMS (Ω)

Resistance

Opposition to current flow — lives in cable, soil, and connections.

$$V = I \times R$$

EC-002 unpacks Ohm's Law from every angle.

OHM'S LAW

The relationship that ties voltage, current, and resistance.

$$V = I \times R$$

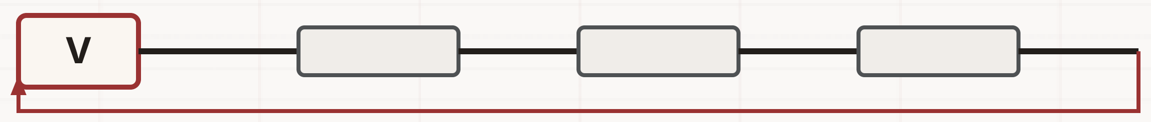
V	I	R
Voltage	**Current**	**Resistance**
VOLTS	AMPERES	OHMS (Ω)
$V = I \times R$	$I = V \div R$	$R = V \div I$

EC-002 unpacks Ohm's Law from every angle, with full practice problems.

SERIES CIRCUITS

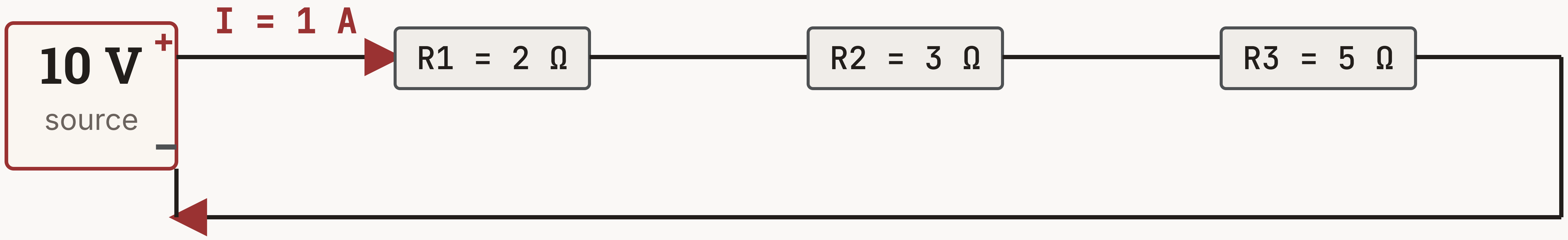
One path, one current.

A series circuit has only one path for current to flow. Every element sits end-to-end on that single path. If the path opens anywhere, everything downstream stops.



SERIES CIRCUITS

Series — one path, one current



Same 1 A flows through every element.

Current is the same

I_T = I_1 = I_2 = I_3

Resistances add

R_T = 2 + 3 + 5 = 10 Ω

Drops sum to source

V_T = V_1 + V_2 + V_3 = 10 V

SERIES CIRCUITS

The three series rules

Three core, three reinforcing — the field-tech short list.

1 Same current everywhere

Whatever current leaves the source is the same at every point on the path. `KCL` — there's nowhere else for it to go.

2 Resistances add

$R_T = R_1 + R_2 + R_3 + \dots$

Cable, connections, anode lead — they all add.

3 Drops sum to source

If the source puts out 20 V, all the drops along the path must add to 20 V. `KVL`.

4 Cable runs are series

Every length of conductor between rectifier and groundbed adds resistance. Each connection adds.

5 Connections matter too

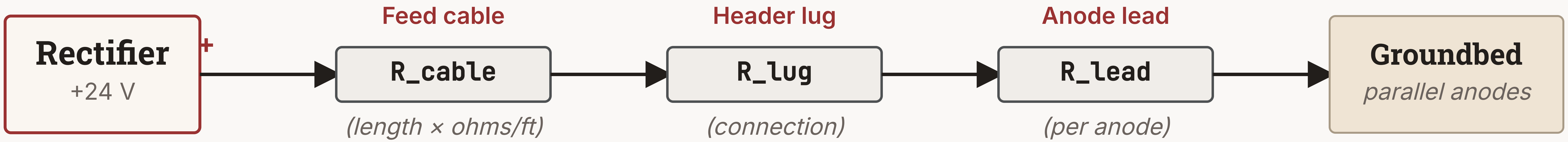
A loose lug or corroded splice is one more series element. Lug torque keeps showing up because it keeps eating voltage.

6 Open path = no current

Break the path anywhere and current stops. High reliability when intact, full failure when broken.

SERIES CIRCUITS · FIELD

In CP work — every cable run is series



All three sit on a single path between rectifier and groundbed.

`R_T = R_cable + R_lug + R_lead`
All on one path

`V_drop = I × R`
Each one consumes voltage

`V_jct = V_source - Σ(IR)`
What reaches the soil

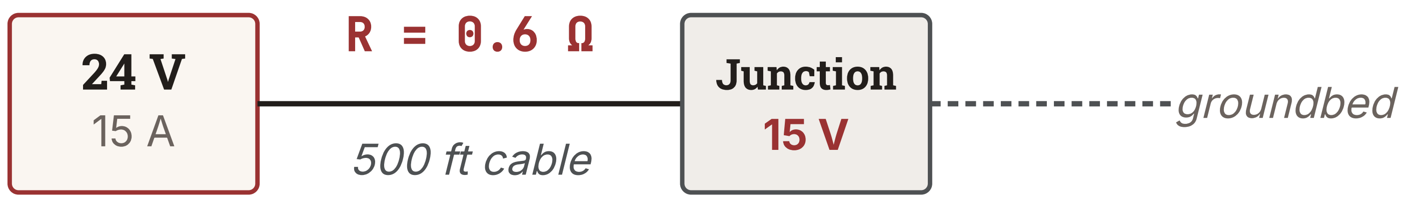
Cable sizing, lug torque, and connection quality all live on the series side. Each one eats your IR-drop budget.

WORKED EXAMPLE · A

A single cable run

500 ft of header cable, 0.6 Ω, carrying 15 A from a 24 V rectifier.

Setup. 500-foot header cable from rectifier to junction box. Cable resistance, given the gauge and length, comes out to **0.6 Ω**. The rectifier is putting **15 A** down the line.



STEP 1 · CABLE RESISTANCE

R = 0.6 Ω

STEP 2 · VOLTAGE DROP

V_drop = 15 A × 0.6 Ω

= 9 V

STEP 3 · WHAT REACHES THE JUNCTION

V_jct = 24 V - 9 V

= 15 V

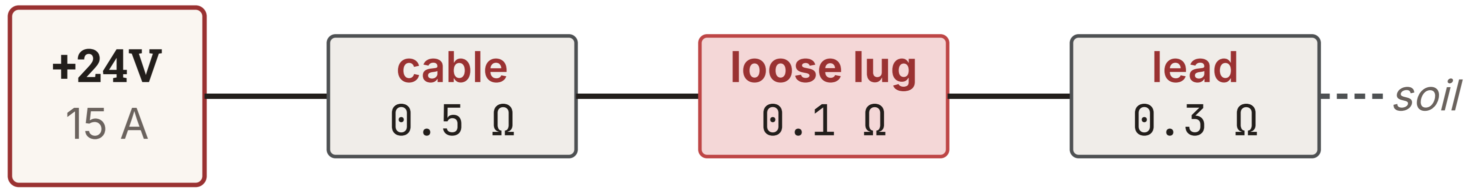
Field implication: *Nine volts the cable consumed before the current ever reached the soil. Only the remaining 15 V is available to push current across the anode-to-soil interface.*

WORKED EXAMPLE · B

Multi-element series

Same path — but with a loose lug in the mix. Three series elements.

Setup. Same path, with a loose lug in the mix. Three series elements: main feed cable, a loose lug at the (+) header junction box terminal, and the anode lead wire. All on the single path from the rectifier to the soil.



STEP 1 · SUM THE RESISTANCES

$R_T = 0.5 + 0.1 + 0.3$

$= 0.9\ \Omega$

STEP 2 · TOTAL VOLTAGE DROP

$V_{drop} = 15\ A \times 0.9\ \Omega$

$= 13.5\ V$

STEP 3 · WHAT'S LEFT

$V_{jct} = 24\ V - 13.5\ V$

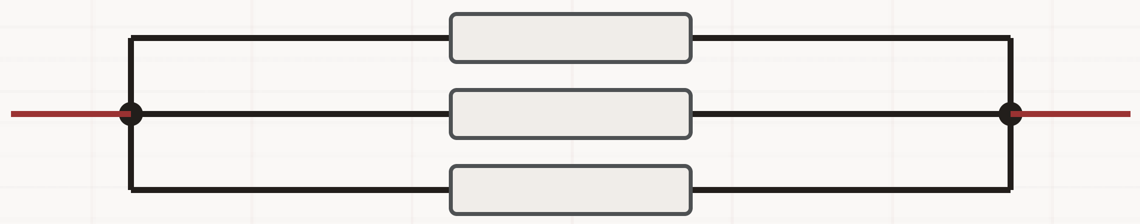
$= 10.5\ V$

Almost a third more loss than the cable alone. **Each element adds. Each connection adds.**

PARALLEL CIRCUITS

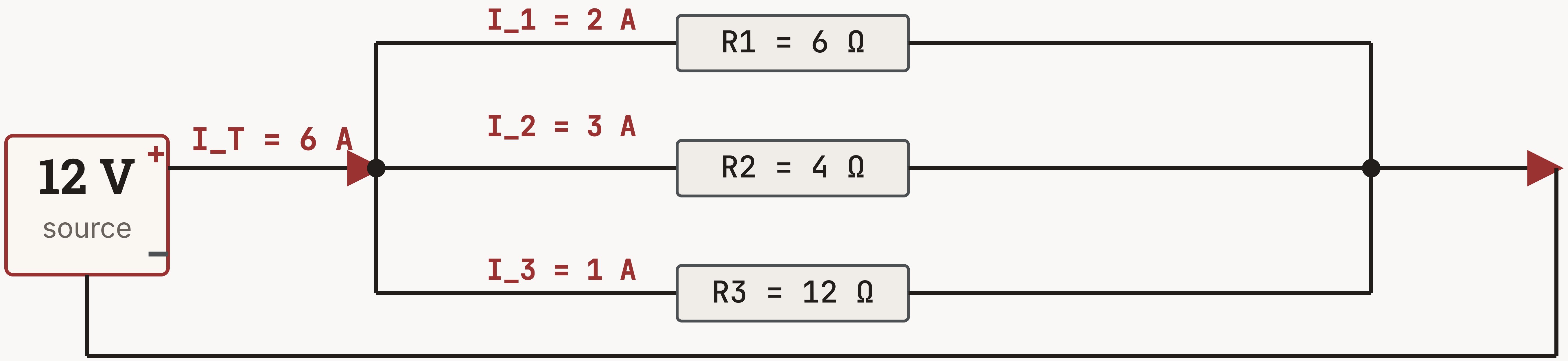
Many paths, shared voltage.

A parallel circuit gives current more than one route between the same two points. Each branch sees the same voltage. Total current is the sum of the branch currents, and total resistance always drops below the smallest branch.



PARALLEL CIRCUITS

Parallel — many paths, shared voltage



Voltage is the same

$V_T = V_1 = V_2 = V_3 = 12\ V$

Branch currents add

$I_T = 2 + 3 + 1 = 6\ A$

Total drops below smallest

$R_T = 12 / 6 = 2\ \Omega < 4\ \Omega$

PARALLEL CIRCUITS

The three parallel rules

Three core, three reinforcing — counterparts to the series list.

1 Same voltage on every branch

All branches are tied to the same two nodes, so they all see the same voltage. `KVL` across each loop gives the same answer.

2 Branch currents add

$I_T = I_1 + I_2 + I_3 + \ldots$

Whatever leaves the node has to come back. `KCL`.

3 Total resistance falls

Adding paths gives current more places to flow. R_T is always less than the smallest branch.

4 Anodes in a groundbed are parallel

Each anode is a separate path from header to soil. They share the header voltage; their currents add at the header.

5 Equal branches divide evenly

If every branch has the same resistance, current splits equally. Unequal anode-to-soil R, unequal anode current.

6 One open branch ≠ failure

Lose one anode and the others keep working. Total current drops; the rest pick up the load. Redundancy by design.

PARALLEL CIRCUITS · MATH

Computing parallel resistance

The general reciprocal form — and the two-branch shortcut.

GENERAL · ANY NUMBER OF BRANCHES

Reciprocal sum

```
1 / R_T = 1/R_1 + 1/R_2 + 1/R_3 + …
```

Add the reciprocals (conductances), then invert. Works for **any number of branches**. Each branch contributes additional conductance, so R_T can only fall.

```
Example: 1/R_T = 1/6 + 1/4 + 1/12
= 2/12 + 3/12 + 1/12 = 6/12
R_T = 2 Ω
```

SHORTCUT · EXACTLY TWO BRANCHES

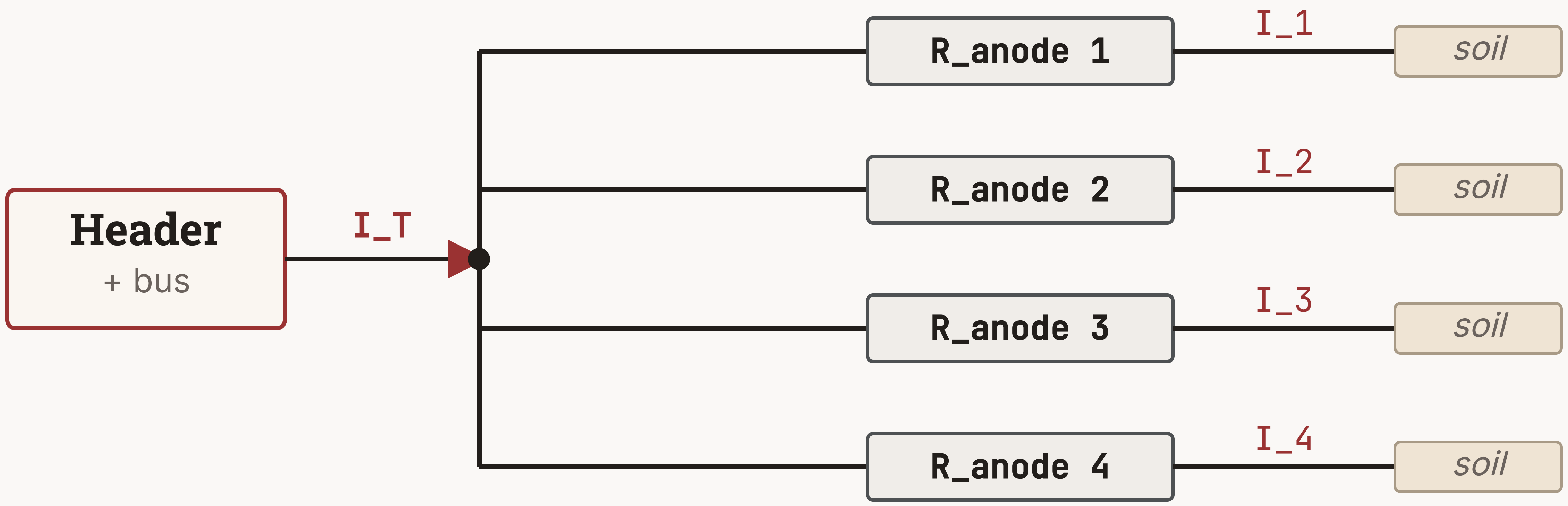
Product over sum

```
R_T = (R_1 · R_2) / (R_1 + R_2)
```

A clean substitution of the reciprocal form when you have **exactly two** branches. Memorize this — most field problems involving paralleled cables or two anode banks reduce to it.

```
Example: R_1 = 6 Ω, R_2 = 4 Ω
R_T = (6 × 4) / (6 + 4)
= 24 / 10 = 2.4 Ω
```

In CP work — the groundbed is parallel



Each branch:

```
same V_header
own R_anode-soil
own branch I
```

At the header:

$I_T = I_1 + I_2 + I_3 + I_4$

Add a path, lose resistance

More anodes ⇒ lower R_groundbed. That's the whole point of multi-anode beds.

Unequal branches, unequal current

If one anode-to-soil R climbs (drying soil, polarization), that branch carries less current. Others compensate.

Open branch, system survives

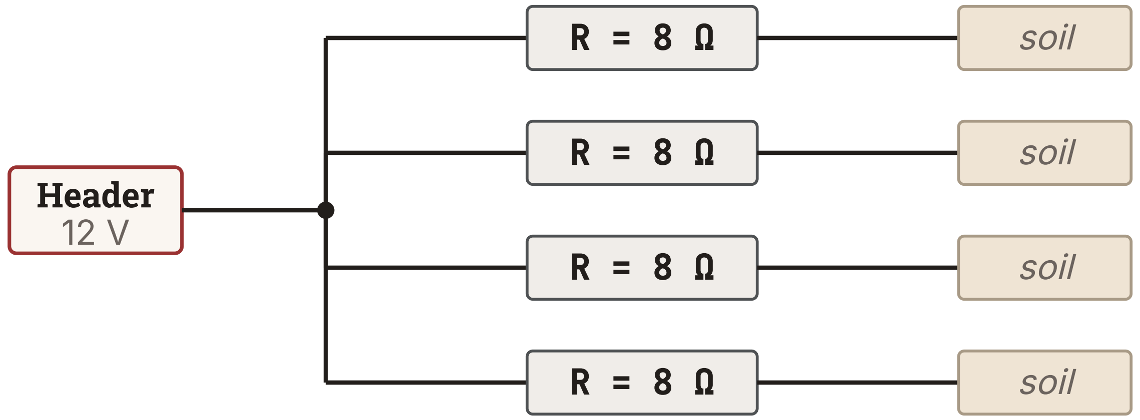
Lose one anode lead and the rest keep flowing. The redundancy lives on the parallel side.

WORKED EXAMPLE · C

A four-anode groundbed

Each anode-to-soil resistance is 8 Ω. Header is at 12 V.

Setup. A groundbed with **four identical anodes**, each measuring 8 Ω from anode metal to remote earth. The header bus is held at 12 V relative to the structure. Equal branches in parallel — find total groundbed resistance, total current, and per-anode current.



STEP 1 · GROUNDBED RESISTANCE

$1/R_T = 4 \times (1/8) = 4/8$

$R_T = 2\ \Omega$

STEP 2 · TOTAL CURRENT

$I_T = 12\ V / 2\ \Omega$

$= 6\ A$

STEP 3 · PER-ANODE CURRENT

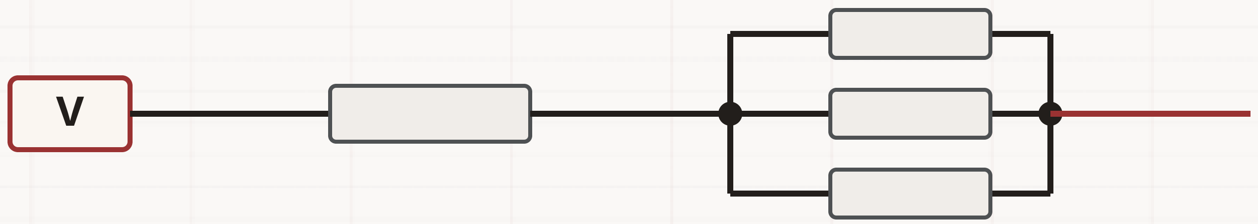
$I_{branch} = 6\ A / 4 = 1.5\ A$

Four 8 Ω anodes in parallel → **2 Ω total***, with each branch carrying 1.5 A.*

PUTTING IT TOGETHER

A real circuit is both.

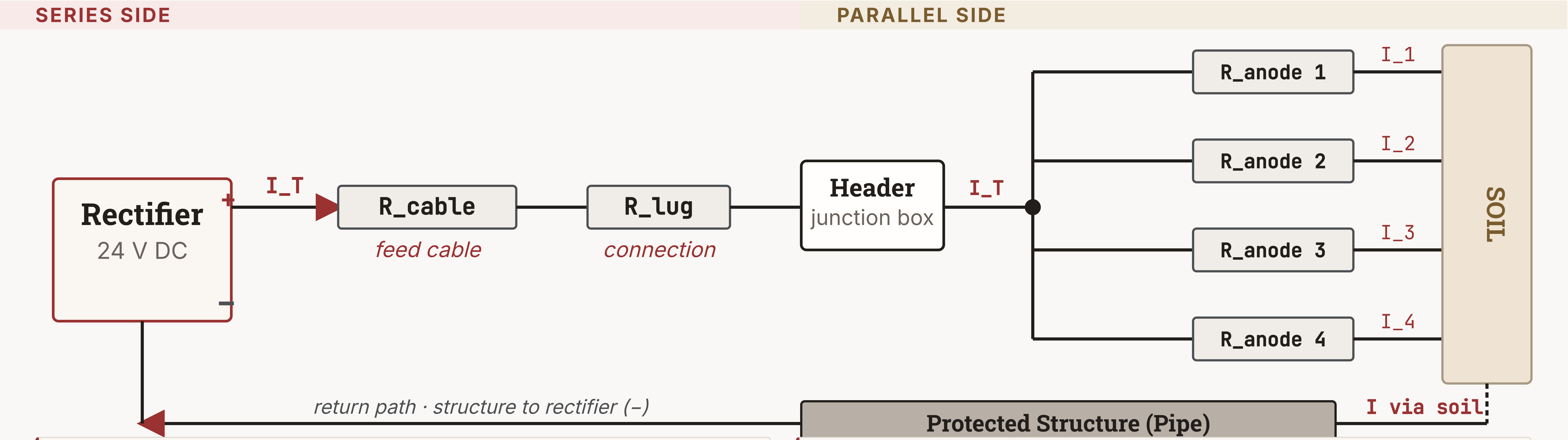
Every CP system is a **series-parallel** mix. The cable runs from rectifier to junction box are series. The anodes in the bed are parallel. The two halves sit end-to-end on the same loop — and you analyze them by reducing inward.



CP CIRCUIT · SYNTHESIS

Series cable, parallel groundbed

The whole impressed-current loop, labeled. Series on the left of the junction; parallel on the right.



Series side · adds resistance

R_cable + R_lug stand between the rectifier and the header. Every drop here is voltage you don't get to spend on driving current into soil.

Parallel side · divides current

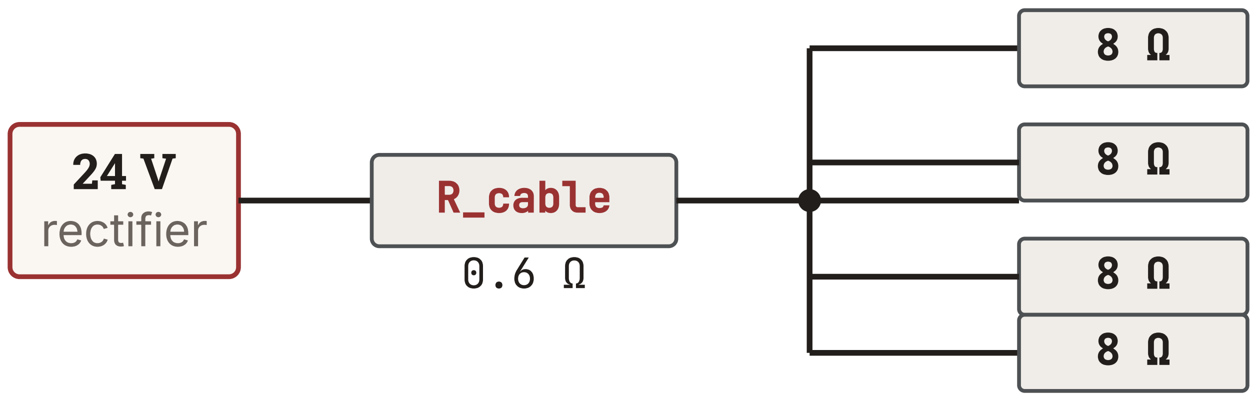
Each anode-to-soil path is a branch. Their conductances add. R_groundbed always falls below the smallest branch.

WORKED EXAMPLE · D

Reduce, then solve

0.6 Ω feed cable in series with a 2 Ω groundbed, on a 24 V rectifier.

Setup. A series feed cable (0.6 Ω) drops voltage on the way to the header. From there, a parallel groundbed of four 8 Ω anodes returns current through soil. The whole loop is on a 24 V rectifier. Reduce the parallel side first, then sum the series, then apply Ohm's law to get total current.



STEP 1 · REDUCE PARALLEL

R_gb = 8 / 4 = **2 Ω**

STEP 2 · SUM SERIES

R_T = 0.6 + 2.0 = **2.6 Ω**

STEP 3 · TOTAL CURRENT

I_T = 24 V / 2.6 Ω ≈ **9.2 A**

Reduce inward. *Collapse the parallel side to one number, add the series, then divide. The hard problem becomes three small ones.*

SERIES-PARALLEL · SENSITIVITY

What changes when the field changes?

Same 24 V rectifier, same 4-anode bed. Three field-realistic perturbations.

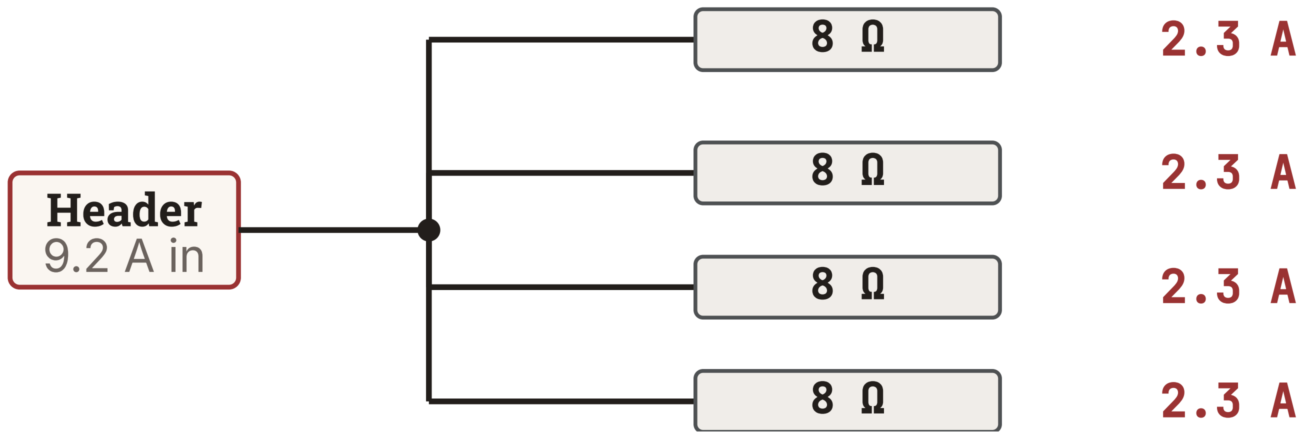
A loose lug + 0.1 Ω in series	R_T : 2.6 Ω → 2.7 Ω I_T : 9.2 A → 8.9 A	**Small in isolation, costly across many connections.** Three loose lugs in the same path stack to nearly a full amp lost.
An anode dries out R_anode 8 Ω → 16 Ω	R_gb : 2.0 Ω → 2.29 Ω I_T : 9.2 A → 8.3 A	**Branches share the load — but unequally now.** The dry anode carries less; the others compensate, accelerating their consumption.
An anode opens lead severed, 1 of 4 lost	R_gb : 2.0 Ω → 2.67 Ω I_T : 9.2 A → 7.3 A	**System survives, output drops.** The remaining three anodes carry 25% more each, shortening their life. Redundancy buys time, not immunity.

WORKED EXAMPLE · E

Per-anode current and life

From the previous result — what current does each anode carry, and what does that mean for life?

Setup. Continuing from Example D: 9.2 A total flowing through the 4-anode parallel bank. All four anodes equal at 8 Ω each, so they share evenly. With each anode rated for 1 lb/yr per amp of consumption (typical for high-silicon cast iron), what does that imply for service life?



STEP 1 · PER-ANODE CURRENT

I_branch = 9.2 / 4 = **2.3 A**

STEP 2 · ANNUAL LOSS PER ANODE

2.3 A × 1 lb/A·yr = **2.3 lb/yr**

STEP 3 · LIFE FROM A 50 LB ANODE

50 / 2.3 ≈ **22 yr**

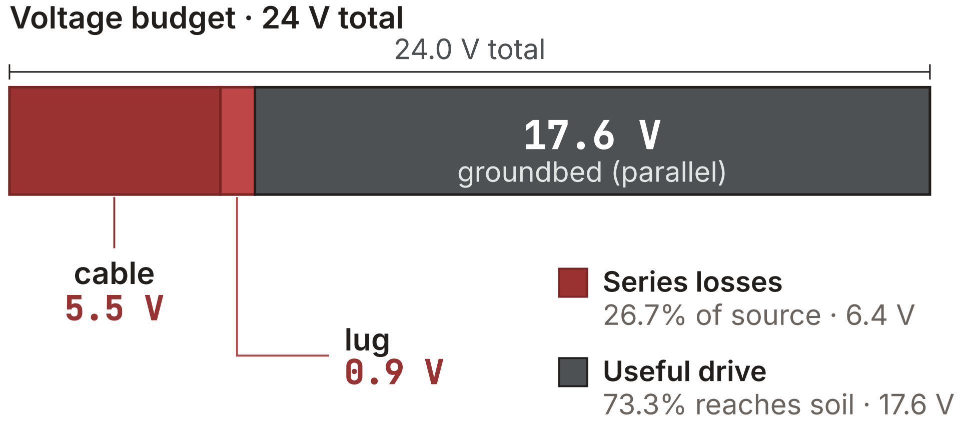
Equal anodes share equally. Once the assumption breaks — drying soil, polarization, broken lead — branches diverge and life drops fast on whichever one carries the most.

WORKED EXAMPLE · F

Voltage budget across the loop

Where do the 24 V actually go? Tracking the drop across each block of the loop.

Setup. Same circuit, 9.2 A flowing. Account for the 24 V across each block: feed cable, header lug, and the parallel groundbed (which now appears as one equivalent 2 Ω). Drops should sum to 24 V — KVL holds for the whole loop.



STEP 1 · CABLE DROP

V_cable = 9.2 × 0.6 = **5.5 V**

STEP 2 · LUG DROP

V_lug = 9.2 × 0.1 = **0.9 V**

STEP 3 · GROUNDBED DROP

V_gb = 9.2 × 2.0 = **17.6 V**

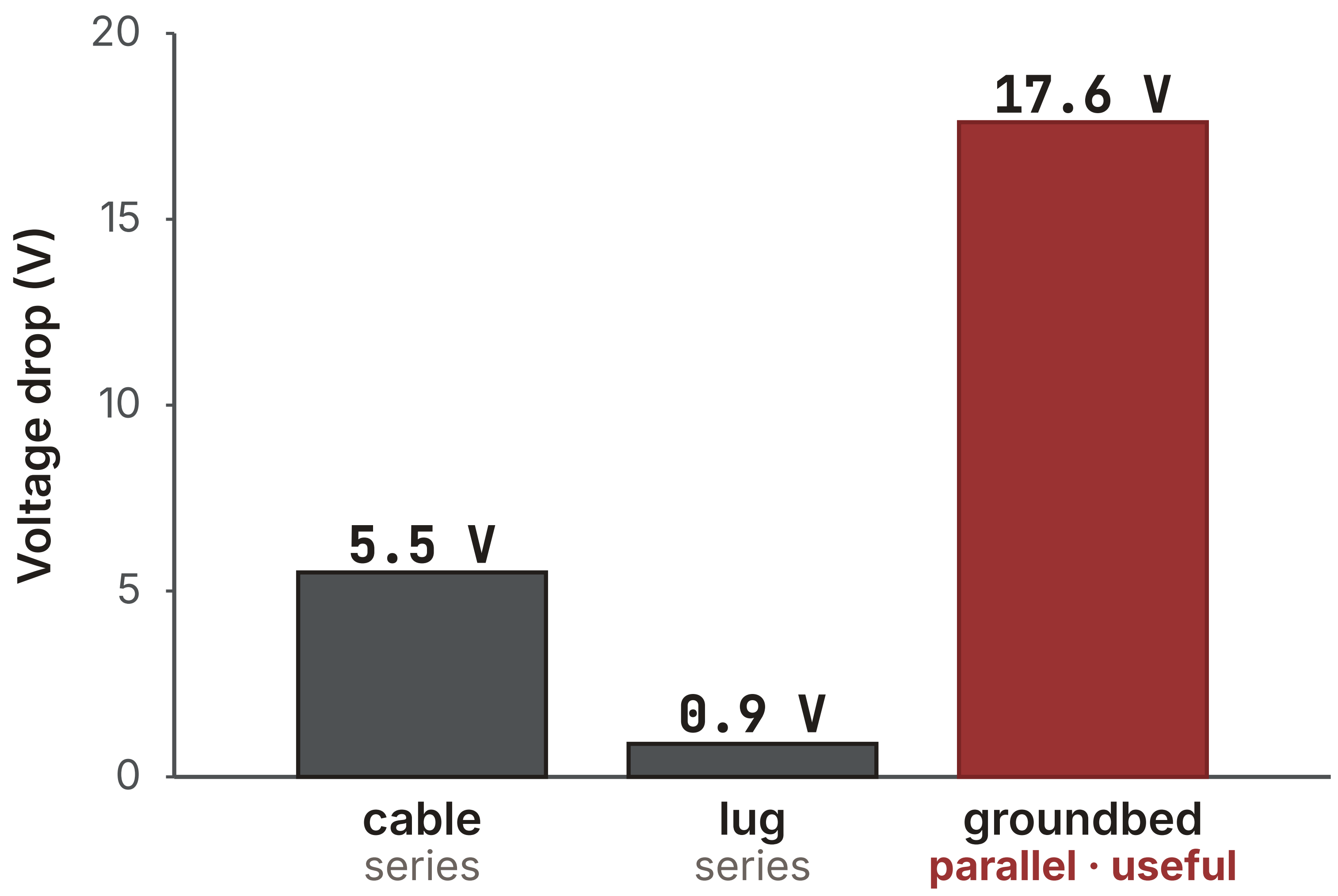
Σ = 5.5 + 0.9 + 17.6 = 24.0 V ✓

Series steals; parallel delivers. *The 6.4 V lost to cable + lug never reaches soil. Tighten lugs, size cable up — those volts come back.*

INSIGHT

Where the work happens

Voltage drop by element · 24 V source, 9.2 A



THE FIELD LESSON

The voltage you spend on the soil is the voltage doing the protection.

In a healthy CP system, the **parallel side dominates** the voltage budget. Most of the 24 V should reach soil — that's what drives current across the anode-to-soil interface and onto the structure.

When the **series bars start growing** — fatter cable drop, fatter lug drop — the soil's share shrinks. Same source, less protection. **That is the failure mode.**

SYNTHESIS · HOOK RESOLVED

Back to the 6 amps that vanished

FIELD READINGS · TODAY

Rectifier output	12.0 V · 8.0 A
Voltage at junction box	11.1 V
Drop on feed cable	0.9 V
Inner anodes (each)	≈ 1.9 A
Outer anodes (each)	≈ 1.05 A
last visit · same dial	14.0 A
current loss since	-6.0 A

Three findings, one diagnosis.

1. **Cable IR drop is real, but small.** 0.9 V on the feed cable is a 7.5% series tax — annoying, not the killer.
   `V_cable = 8.0 A × R_cable ≈ 0.11 Ω · series side`

2. **Groundbed resistance has climbed.** Same 11.1 V driving the bed used to push 14 A; now it pushes 8 A. R_groundbed went from ≈ 0.79 Ω to **≈ 1.39 Ω** — the parallel branches lost conductance.
   `R_gb = V_gb / I_T = 11.1 / 8.0 = 1.39 Ω`

3. **Imbalance points to the dry branches.** Inner anodes carrying ~80% more than outer ones means outer-bed soil dried out — the outer branches grew their R, current shifted inward.
   `Branches share by conductance · I ∝ 1/R`

Not a rectifier problem. Not a soil problem alone. **A circuit problem with a soil cause** — and the shape told you where to look.

THE PROCEDURE

Reduce any CP circuit in five steps

Carry this sequence in your head. Run it on paper, in the truck, at the station.

1

IDENTIFY THE SHAPE

Find the parallel groups. What's left is series.

```
parallel: branches
share two nodes

series: one path,
no branches
```

Trace from rectifier (+) to (–) — branch points are parallel anchors.

2

REDUCE THE PARALLEL GROUPS

Collapse each parallel block to one equivalent R.

```
1/R_p = Σ 1/R_i

n equal branches:
R_p = R / n
```

R_p is always less than the smallest branch. Sanity-check by inspection.

3

SUM THE SERIES

Add every series element on the loop.

```
R_T = R_cable
    + R_lug
    + R_p
    + R_structure

→ one number
```

Series adds straight; nothing splits.

4

APPLY OHM'S LAW

Total current from the rectifier voltage.

```
I_T = V / R_T

worked example:
24 / 2.6
  = 9.2 A
```

This is the current entering the parallel block; not what each branch carries.

5

WALK BACK · SPLIT & DROP

Distribute current and account for voltage.

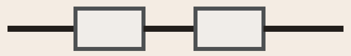
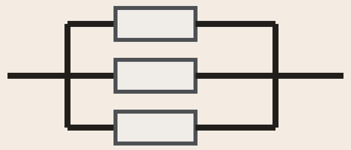
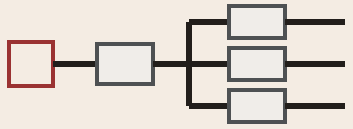
```
per-branch:
I_i = V_p / R_i

per-element:
V_i = I × R_i

KVL check: ΣV =
V_src
```

If the drops don't sum to the source, you missed an element.

FIELD DIAGNOSTIC

Read the shape, find the fault

Where the symptom shows up tells you which side of the circuit is sick.

WHERE THE FAULT LIVES	WHAT YOU SEE IN THE FIELD	WHAT IT MEANS	FIRST MOVE
Series side CABLE · LUGS · STRUCTURE 	**Voltage drops along the loop;** reading at the rectifier doesn't match reading at the junction box. $V_{rect} = 24$ V · $V_{jbox} = 18$ V → 6 V missing	Resistance has grown **somewhere on the path** — almost always a loose lug, a corroded splice, or undersized cable feeding too much current.	**Tighten and meter every connection.** Walk the cable; ohm-out each lug. The fix is mechanical.
Parallel side GROUNDBED · BRANCHES 	**Branches carry uneven current;** total output is down, but rectifier and junction-box voltages still match. I_{total} ↓ · $I_{anode\_1} = 3.2$ A vs. $I_{anode\_4} = 1.1$ A	Conductances have **shifted between branches** — soil drying around outer anodes, or a single anode has consumed and dropped offline.	**Shunt-meter each anode lead.** Map current per branch; the dry or open one names itself.
Both sides at once WHOLE CP LOOP 	**Voltage budget is off and branch currents are uneven.** The 24 V isn't spending where it should, and the share at the bed is wrong. V_{cable} ↑ & I_{anode} imbalance ↑ & I_{total} ↓	Both failure modes overlap — common when an old install has both a deteriorated splice **and** a maturing bed.	**Series first, then branches.** Tighten the loop, then meter the bed. Don't chase both at once.

KNOWLEDGE CHECK

Three quick scenarios

Work each one on paper before peeking. Answers below — try the math first.

Q1 · REDUCE

A 36 V rectifier feeds a 1.2 Ω cable, then a 6-anode bed of 12 Ω anodes in parallel.

```
V = 36 V
R_cab = 1.2 Ω
6 × R_a = 12 Ω each
```

Find R_T and I_T.

ANSWER

R_p = 12 / 6 = **2.0 Ω**
R_T = 1.2 + 2.0 = **3.2 Ω**
I_T = 36 / 3.2 ≈ **11.25 A**

Q2 · DIAGNOSE

Rectifier reads 30 V, 5 A. Junction box reads 30 V. Anode current spread: 1.8, 1.7, 0.3, 1.2 A.

```
ΔV cable ≈ 0 V
I_total = 5.0 A
share = 36/34/6/24 %
```

Where's the fault — series, parallel, or both?

ANSWER

Cable is fine (0 V drop). One branch carries only 0.3 A — that anode has gone **high-R** (drying or near end of life). **Parallel side · single branch.**

Q3 · PREDICT

In Q1's circuit, what voltage is available at the header to drive the bed?

```
I_T = 11.25 A
R_cab = 1.2 Ω
V_src = 36 V
```

Compute V_header and the % reaching soil.

ANSWER

V_{cable} = 11.25 × 1.2 = **13.5 V**
V_{header} = 36 − 13.5 = **22.5 V**
Useful drive: **62.5%** · the cable is eating too much — **upsize it**.

EC-001 / LESSON 2 · CLOSE

You can now read a CP circuit by its shape.

- ✓ **Recognize** series, parallel, and series-parallel patterns in any CP loop.
- ✓ **Predict** what stays common and what splits before opening a single junction box.
- ✓ **Reduce** a series-parallel circuit to one equivalent resistance using the 5-step procedure.
- ✓ **Read** field symptoms by side — series IR drop versus parallel imbalance.
- ✓ **Use** Ohm's law and IR-drop math to predict voltage available at the bed.

NEXT LESSON

EC-001 / L3

Soil resistivity, anode-to-earth resistance & the Dwight equation

We've treated R_{anode} as a number. Next, we open it up — what determines how hard a single anode pushes current into the earth, and how the soil itself sets the ceiling on every CP system you'll ever commission.

The circuit doesn't lie. Your job is to listen to the shape.

