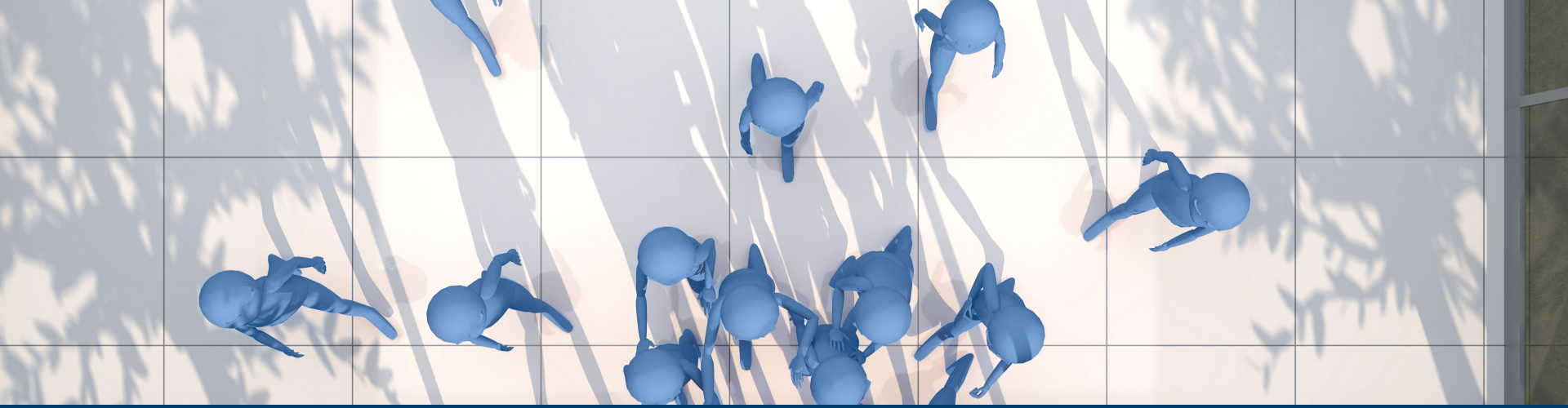


SCIENTIFIC WORKING

What is science?

21 October 2026 | Mohcine Chraibi, Armin Seyfried
Forschungszentrum Jülich and University of Wuppertal

BERGISCHE UNIVERSITÄT WUPPERTAL
JÜLICH Forschungszentrum

HOW DO WE GAIN SCIENTIFIC KNOWLEDGE?

And how do we recognise a good explanation?

Today we investigate a puzzle from traffic planning

What happens when a city builds a new road?

With this example we learn how science explains problems, derives predictions and tests its explanations critically.

DISCUSSION

Why do we know things today that nobody knew 300 years ago?

And how can we understand things we have never observed?

WHY DOES THE EARTH QUAKE?

Two explanations for the same observation

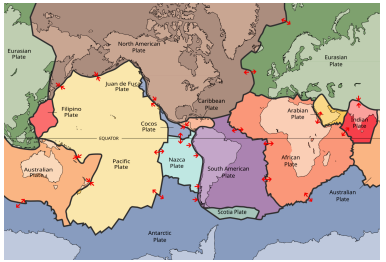
Traditional story

The earth rests on a giant bull. When it moves, the earth quakes.



Plate tectonics

Plates of the earth's crust move. At their boundaries, stresses build up and are released abruptly.



Both seem to explain why the earth quakes. Why is the second explanation better?

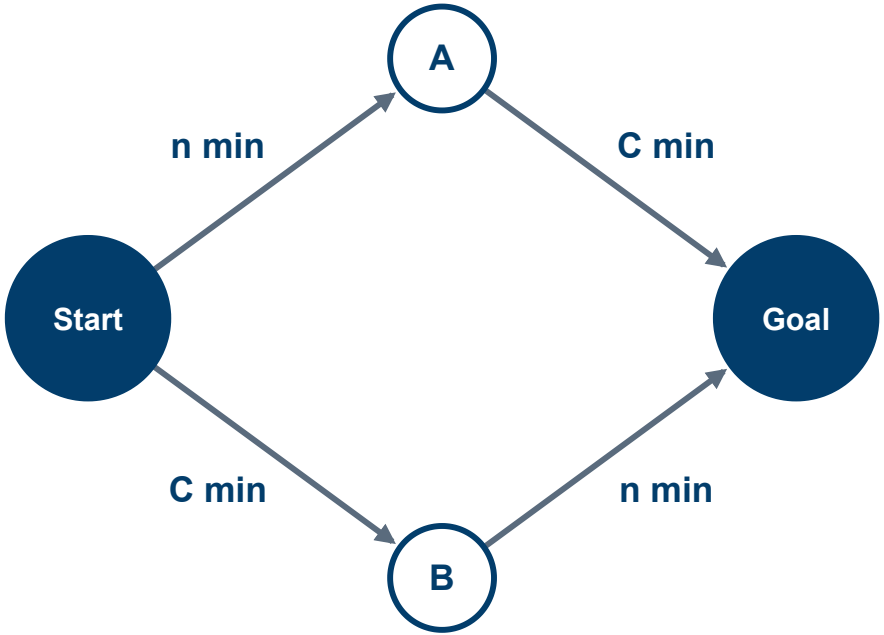
Bull, elephant or dragon: the story explains just as much with any animal. Plate tectonics cannot be changed at will; it depends on measurable movements, rocks and mechanisms.

Progress does not just mean observing more. It means developing better explanations and testing them critically.

Miniature from al-Qazwīnī's cosmography (1595); map: USGS. Both public domain (Wikimedia Commons).

A GAME

Round 1: Upper or lower?



You want to reach the goal quickly.

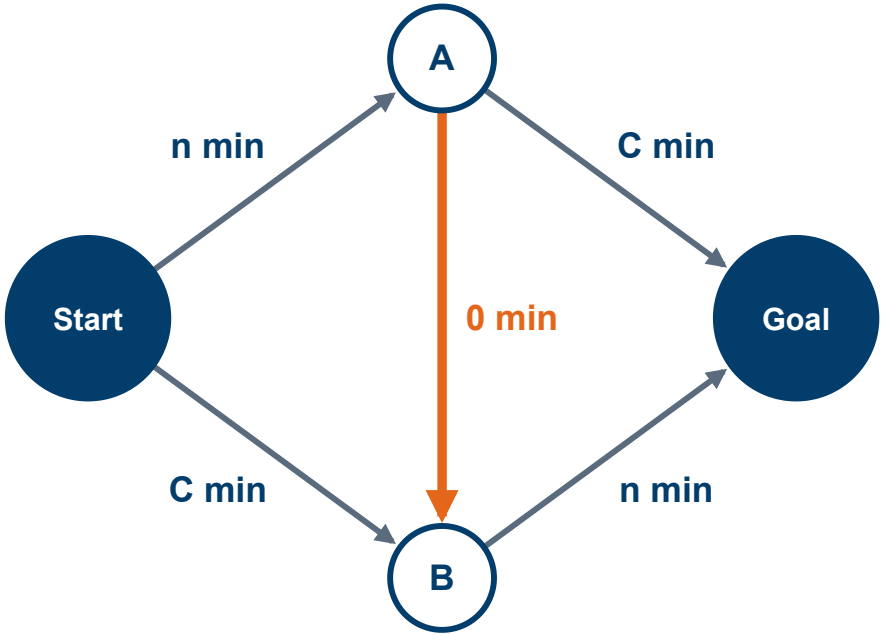
People in the room: 15 **→ C = 17 min**

- n = number of drivers on this road
- C = people in the room + 2
- Travel time = sum of the roads
- Several rounds: whoever wants to, switches

Write down secretly: upper or lower

A GAME

Round 2: The city builds a shortcut



New road A → B: 0 min

- Three options: upper, lower, shortcut
- Choose secretly again

Are you faster now?

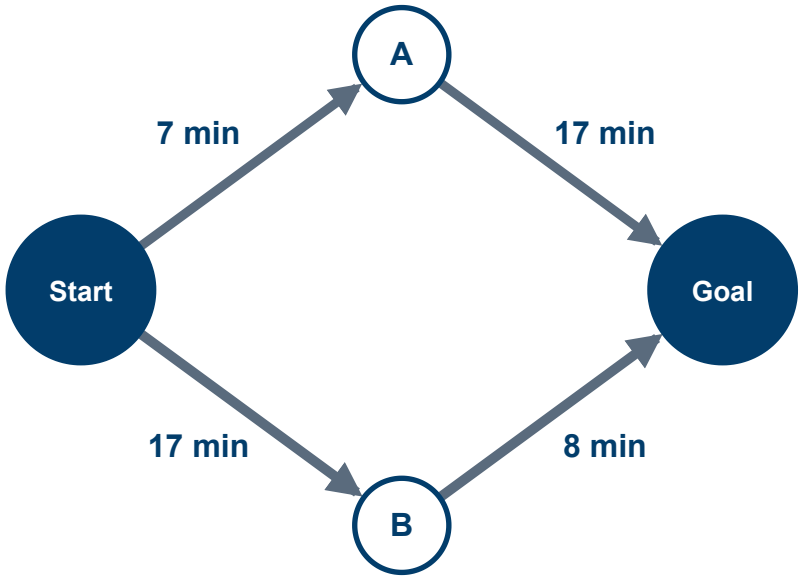
All 15 on the shortcut: **30 min**

Alone back to the upper route: 15 + 17 = **32 min**

Nobody switches away: Nash equilibrium.

TRY IT YOURSELF

Move the drivers: where does it settle?



People N 15 C = N + 2 = 17 ☐ Shortcut A → B

upper: **7**

lower: **8** (rest)

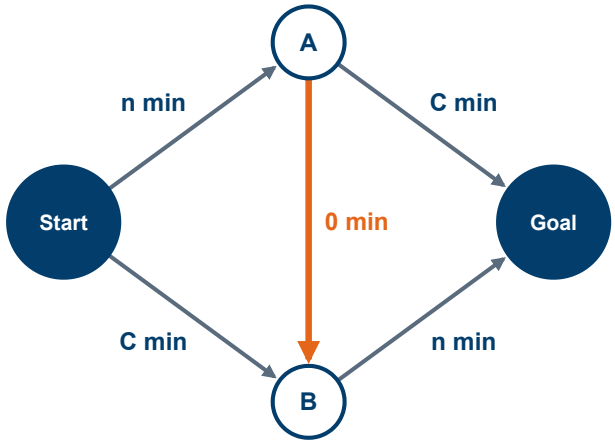
upper	**24 min**
lower	**25 min**

Average of all drivers: **24.5 min**

Equilibrium: nobody can improve alone.

BRAESS PARADOX

Dietrich Braess, 1968: our game has a name



The same network structure as in Braess' paper

1952	Wardrop: in equilibrium, all used routes are equally fast.
1968	Braess, mathematician in Münster: an additional road can make everyone slower. *"Über ein Paradoxon aus der Verkehrsplanung"*
1991	Cohen & Horowitz: the same paradox with springs and strings
2005	English translation: widely accessible internationally
today	An argument in traffic planning: more roads do not automatically help.

Wardrop (1952), Proc. ICE II 1(3); Braess (1968), Unternehmensforschung 12, 258–268; Cohen & Horowitz (1991), Nature 352, 699–701; Braess, Nagurney & Wakolbinger (2005), Transportation Science 39(4), 446–450.

BRAESS PARADOX

A new road makes everyone slower

24–25 min → **30 min**

without shortcut | with shortcut

15 people, C = 17

Everyone chooses the fastest route for themselves, and the result is worse for all. **That is what our model predicts.**

But does this also hold in reality?

How can we test this prediction scientifically?

What do we now know about our model, and what do we not yet know about reality?

A GOOD EXPLANATION?

Or just a plausible story?

Explanation A

“The new road makes everything worse because drivers are selfish.”

Explanation B

“With the shortcut, the route over both variable roads is the cheapest for each individual. The load there grows until everyone ends up in a worse equilibrium.”

What happens if the shortcut costs 5 minutes?

Does the paradox remain? And when does it disappear?

A good explanation cannot be changed at will without ceasing to explain anything.
David Deutsch, The Beginning of Infinity (2011)

WHAT HAVE WE JUST DONE?

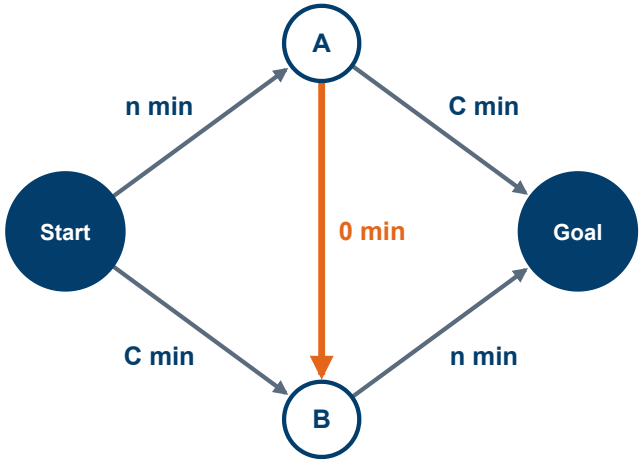
The path for the rest of the lecture

1	**Problem**	What surprised us?
2	**Explanation**	How do we explain it? Model, theory, hypothesis
3	**Testing**	Does our explanation hold? Empirics, experiment, simulation
4	**Improvement**	Where could we be wrong? What really caused it?
5	**Application**	What does this mean for your bachelor thesis?

MODEL

How do we know? **We can explain it. Is the model realistic enough?**

A simplified image of reality



As simple as possible, but complex enough for our question

What did we leave out?

- **People:** not everyone chooses the fastest route
- **Traffic:** traffic lights, junctions, queues
- **Roads:** lengths, widths, capacities
- **Travel time:** why exactly n minutes? (fundamental diagram)
- **Time:** everyone decides at the same time
- **Information:** how does everyone know the travel times?

Is our model therefore bad?

No. It does not have to contain everything, only the essential mechanisms of the question: route choice, load, travel time.

Ockham's razor

If two models explain the observation equally well, the simpler one is preferable.

ASSUMPTION, THEORY, HYPOTHESIS

How do we know? **What would have to happen for us to reject the explanation?**

What we presuppose, what we claim, what we test

Assumption

Drivers choose the route that is fastest for them.

Behavioural assumption, set, not tested

Theory

A coherent, consistent system of statements.

Equilibrium theory of route choice

(Wardrop 1952)

Hypothesis

A concrete prediction that can fail against data.

If road Y in network X is closed, the mean travel time decreases.

Touchstone

Which observation would refute your hypothesis? If you cannot say, it is not yet a hypothesis.

VERIFY OR FALSIFY?

A thousand white swans prove nothing

“All swans are white.”

Every white swan confirms the statement, but does not prove it.

One black swan refutes it.

Karl Popper, Logik der Forschung (1934)

“An additional road **always** shortens travel time.”

confirmed in many cities …

… and refuted by one Braess case

Popper asks: can the statement fail? Deutsch adds: does it explain why it must be so? We look for explanations that do both.

EMPIRICS

Road gone, congestion no worse?

Stuttgart 1969

A new road makes traffic worse. Only when it is closed again does traffic improve.

New York 1990

42nd Street is closed on Earth Day. Congestion, if anything, decreases.

Seoul 2003–2005

An urban motorway is demolished. First traffic gets slower, then many switch to the subway.

An observation after an intervention is not yet an experiment.

What else changed in these cities?

Stuttgart: after Knödel (1969), cited in de.wikipedia.org “Braess-Paradoxon”; Kolata, NYT, 25.12.1990; Chung, Hwang & Bae (2012), Transport Policy 21, 165–178.

EXPERIMENT

Is the new road really to blame?

We observed: with the shortcut everyone takes longer. **How can we test this?**

Trial A · Without shortcut

Everyone chooses between two routes.

Trial B · With shortcut

The same people choose between three routes.

What must we keep constant?

Number of people, travel-time rules, information and as far as possible all other experimental conditions.

An experiment deliberately changes one condition and studies its effect.

EXPERIMENT

Clever Hans: could this horse do arithmetic?



Public demonstration, 1904. From: K. Krall, Denkende Tiere (1912), plate 2. Public domain, Wikimedia Commons.

- Around 1900 a horse answers arithmetic questions by tapping its hoof.
- Many answers are correct.

How would you test whether Hans can really do arithmetic?

Questioner knows the answer	**mostly correct**
Questioner does not know it	**many more errors**
Hans cannot see the questioner	**many more errors**

The observation was correct, the explanation wrong.

Today: blinding, control conditions, experimenter effect

Pfungst, O. (1907): Das Pferd des Herrn von Osten (Der Kluge Hans). Leipzig: Barth.

SIMULATION

When pen and paper are no longer enough

Empirics	Theory	**Simulation**
Observe, measure	Think, model	Solve models numerically

- Our game: 4 nodes, mental arithmetic
- Wuppertal: thousands of nodes, travel time depends nonlinearly on load

→ **Algorithms and software that compute the equilibrium**

IS THE SIMULATION THEREFORE RIGHT?

Our fundamental diagram is right

We have

A fundamental diagram from empirical measurements · a network model with route choice · a simulation that computes travel times

Vote: Can we use this to reliably predict the Braess paradox? Yes or no?

Question 1

The simulation reproduces our analytical solution exactly. Can we trust it?

An important verification test has been passed, but this is not yet validation.

Question 2

It uses an experimentally confirmed fundamental diagram. Can we now trust its network predictions?

Not yet. One valid component does not make a valid overall system.

VERIFICATION AND VALIDATION

How do we know? **Does the program compute correctly? And does the model fit?**

Two different questions for a simulation

Reality ⟷ **Model** ⟷ **Program**

Validation

Does the model describe reality well enough for the intended purpose?

Comparison with measured data

Verification

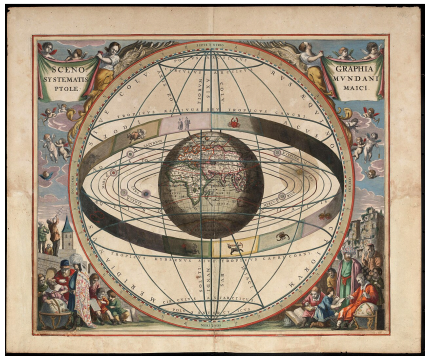
Have we implemented the model correctly and solved it numerically?

Tests, comparison with exact solutions

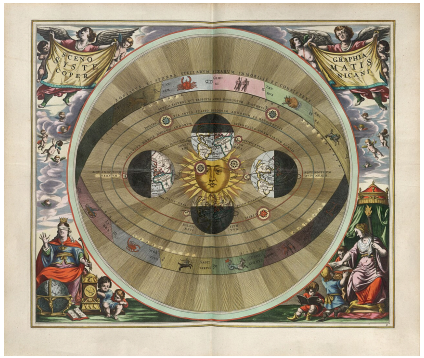
Roache (1998), AIAA J. 36(5), 696–702; AIAA G-077-1998; RiMEA 4.1.1 (2025), Annex 1.

WHAT MOVES AROUND WHAT?

Even a wrong model can predict well



Geocentric (Ptolemy): the earth is at the centre.



Heliocentric (Copernicus): the earth moves around the sun.

Ptolemy predicted planetary positions usefully for centuries. Copernicus was not more accurate at first.

Only Kepler (ellipses, 1609), Galileo (telescope, 1610) and Newton (gravitation, 1687) turned it into the better explanation.

Knowledge grows by improving and replacing models step by step.

Andreas Cellarius, Harmonia Macrocosmica (1660), public domain (Wikimedia Commons).

CAUSALITY

Did the new road cause the congestion?

New road A → B → **Drivers change route** → **More load on the n-roads** → **Everyone slower**

In the game we can show this: same people, same rules, only the road changes.

Seoul: urban motorway demolished --> **Traffic not worse in the long run**

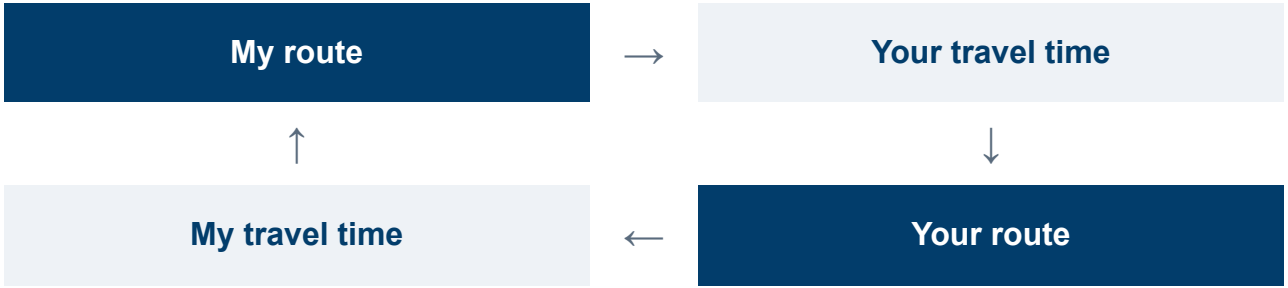
causal?

or switch to the subway, economy …

Temporal order alone proves no cause. You need the comparison: with and without.

INTERACTION

Everyone influences everyone



Physics: the earth pulls the moon, the moon pulls the earth (Newton's third law)

RESEARCH

Basic and applied research merge into each other

Basic research

Extending knowledge, without direct use

Braess 1968: a paradox in graphs

Applied research

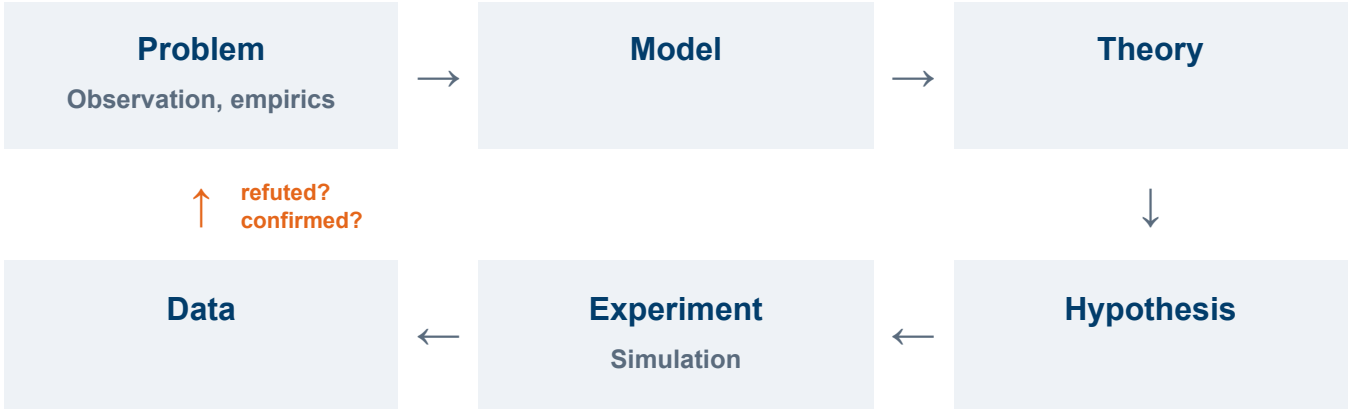
Solving problems, making knowledge usable

Today: an argument against “more roads”

- Grünberg (Jülich): giant magnetoresistance → hard-disk read head
- Theory of relativity → GPS
- Applied research → standards and guidelines (DIN, FGSV, VDI)

SUMMARY

How the concepts fit together



TRANSFER

Task: The same thinking, a completely different theory

> “… the fact that they have been transformed into a crowd puts them in possession of a sort of collective mind …”
>
> Gustave Le Bon, The Crowd (1895; English translation 1896)

Thought experiment 1

You are a Dortmund fan in the Bayern Munich block. Dortmund scores in the last minute. What do you feel?

Thought experiment 2

Your 11-year-old daughter goes to a K-pop concert with her grandfather. Does the grandfather get hypnotised?

Apply the thinking from the traffic example to Le Bon: what exactly is explained? Which mechanism lies behind the “collective mind”? Which observation would refute the claim? Worksheet in Moodle.

AND YOUR BACHELOR THESIS?

Where does your topic lie on this map?

YOUR BACHELOR THESIS

How do we know? **What would convincingly support your claim?**

Task: Place your topic

	Empirics	Theory / model	Simulation
Basic		Braess 1968	
Applied			Traffic planning with simulation

Afterwards: short abstract (¼ page) on your topic or preferred topic.

WHAT HAVE WE LEARNED TODAY?

Not just something about traffic, but how science works

1. We want to understand the world.
2. We discover something surprising.
3. We look for an explanation.
4. We test whether our explanation holds.
5. We improve our knowledge and apply it.

Problem → Explanation → Testing → Improvement → Application

Scientific knowledge is

provisional, testable, methodically grounded and correctable.

Once more: why do we know more today than 300 years ago?

Science does not mean possessing final answers. It means developing explanations, discovering errors and thereby finding ever better explanations.

Further reading: David Deutsch, *The Beginning of Infinity* (2011)

OUTLOOK

At the end of the semester you test a hypothesis yourself

Bottleneck 3 m wide and 1 m long
or 1 m wide and 3 m long: which is better?

Same area, same walking direction. And what does “better” mean: higher flow, shorter evacuation time, lower density in front of the bottleneck?