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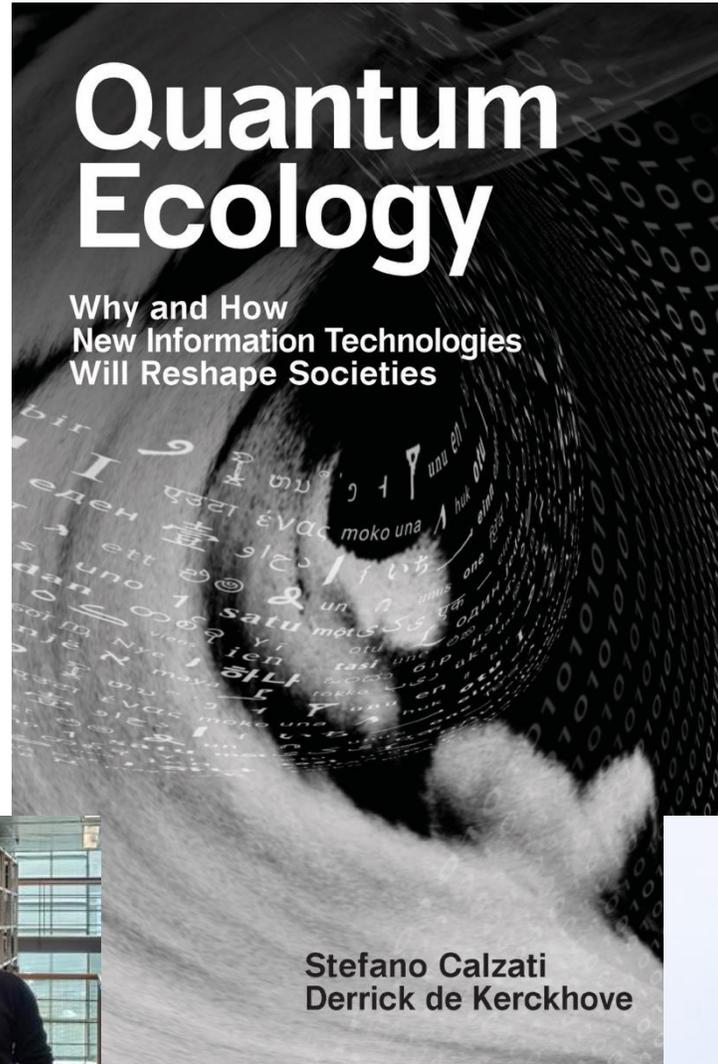
Quantum Ecology

Ideas for Innovative Policymaking and the
Governance of Quantum Information Technologies

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Quantum Ecology

[Calzati & de Kerckhove 2024](#), MIT Press



Onto-epistemological framework, whose pillars are, among others, uncertainty, complementarity, superposition, entanglement.

Technological paradigm, pivoting around emerging Quantum Information Technologies (QITs).

Philosophy of science and technology
→ *social sciences*



Some fundamentals



Principles: uncertainty and complementarity

- **Uncertainty** (Heisenberg 1927): it is **not** possible to measure **simultaneously** and **with maximum precision** two properties of a particle, e.g., position & spin.

→(epistemological “indeterminacy”).

- **Complementarity** (Bohr 1928): “Evidence obtained under different conditions cannot be comprehended within a single picture but must be regarded as complementary.”

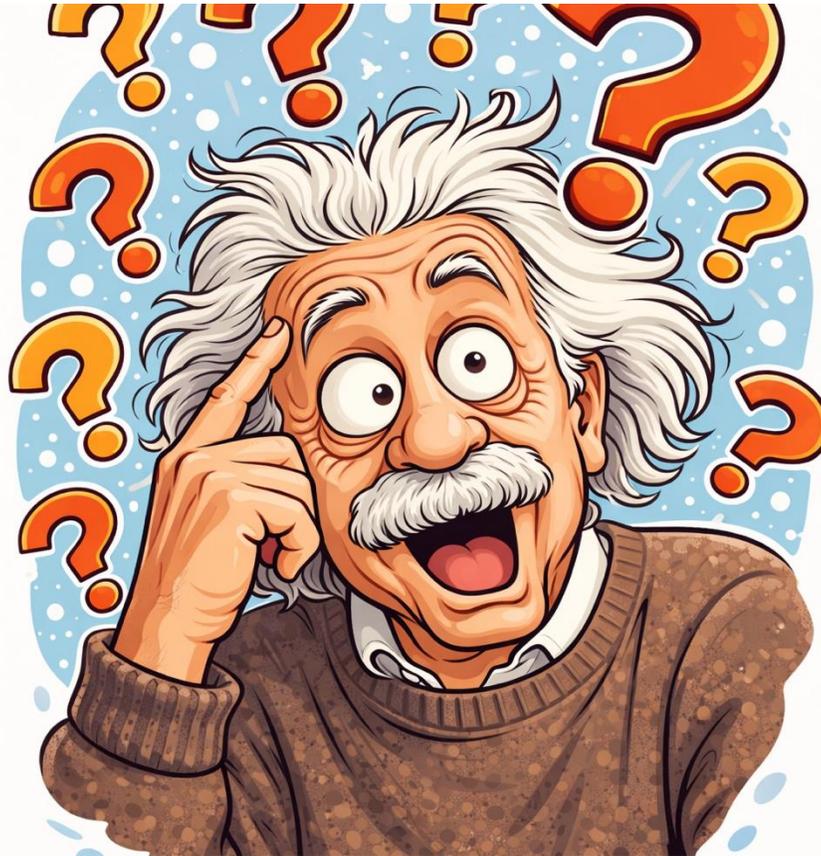
→the whole act of observation **determines** the phenomenon being observed (**ontological** frame; cf. [Barad 2007](#)).



"Niels Bohr and Werner Heisenberg, a German physicist"
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Phenomena: superposition and entanglement



- **Superposition**: until they are measured, particles are probabilistically in overlapping states (e.g., spin up & spin down). Measurement **determines** their state.
→ (collapse of the wave function).
- **(“spooky”) Entanglement**: When two particles are entangled, the measurement of one of them (e.g., spin) **instantly** affects the other particle, irrespective of any distance (**non-locality**).
→ the two particles as one whole system.



Wigner's friend thought experiment

- 1) Wigner's friend performs the measurement of a particle (e.g., spin) inside a laboratory.
- 2) For her, the measurement yields a definite outcome (e.g., spin up).
- 3) For Wigner, who is outside the lab and treats the entire scenario as a quantum system, the outcome is not definite yet, i.e., still in superposition.

→ **Configurational realism**: Different observers can assign different "real" states to the same system → **no observer-independent physical phenomenon**.

→ **Relational epistemology**: Two observers can hold **complementary** but **equally valid** knowledge claims about a phenomenon.



["1979 Nobelpreisträgertagung Physik; Bayrisches Frühstück \(26.6.79\)- am Tisch Paul Dirac, Eugene Wigner - LABW - Staatsarchiv Freiburg W 134 Nr. 113932b"](#) by [Willy Pragher](#) is licensed under [CC BY 4.0](#).

Evidence as insight



His Holiness the 14th Dalai Lama of Tibet listens carefully to his beloved 'science teacher', the physicist Professor David Bohm, at 'Art meets Science and Spirituality in a changing Economy', Stedelijk Museum, Amsterdam, 1990, initiated by Louwrien Wijers.

["His Holiness the 14th Dalai Lama of Tibet listens carefully to his beloved 'science teacher', the physicist Professor David Bohm, at 'Art meets Science and Spirituality in a changing Economy' | Louwrien Wijers"](#) by [NOK Kunst](#) is licensed under [CC BY-NC-ND 2.0](#).

"We have to remember that what we observe is not nature itself, but nature **exposed to our method of questioning.**" ([Heisenberg 1958](#))

"**All theories are insights,** which are neither true nor false but, rather, **clear in certain domains, and unclear when extended beyond these domains.**" ([Bohm 1980](#))

From **evidence** (*ex-videre* "to see out of something") to **foresight** (*fore-sikh*: "to see in advance") and **insight** (*in-sekh*: "to see into something").



Quantum-based techs & QITs

Quantum sensing

- 1) magnetic resonance imaging (MRI)** exploits the spin of the proton in the hydrogen's nucleus by applying a magnetic field to make the spin flip.
- 2) atomic clock** measures time by counting oscillations of electrons when excited (i.e., receive or lose energy).

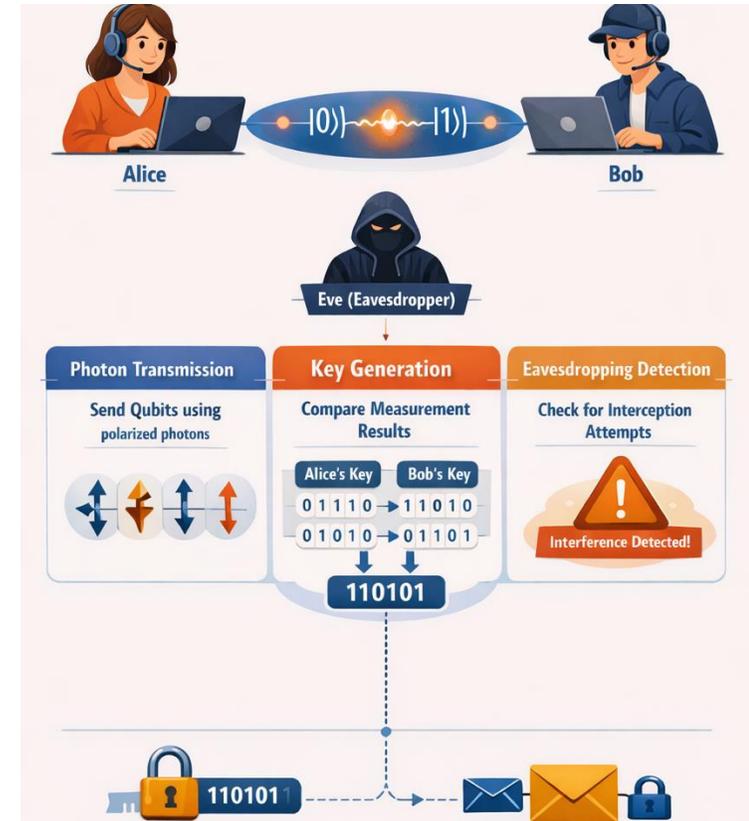
Quantum information techs

- a) quantum communication**
- b) quantum computer**



Quantum communication

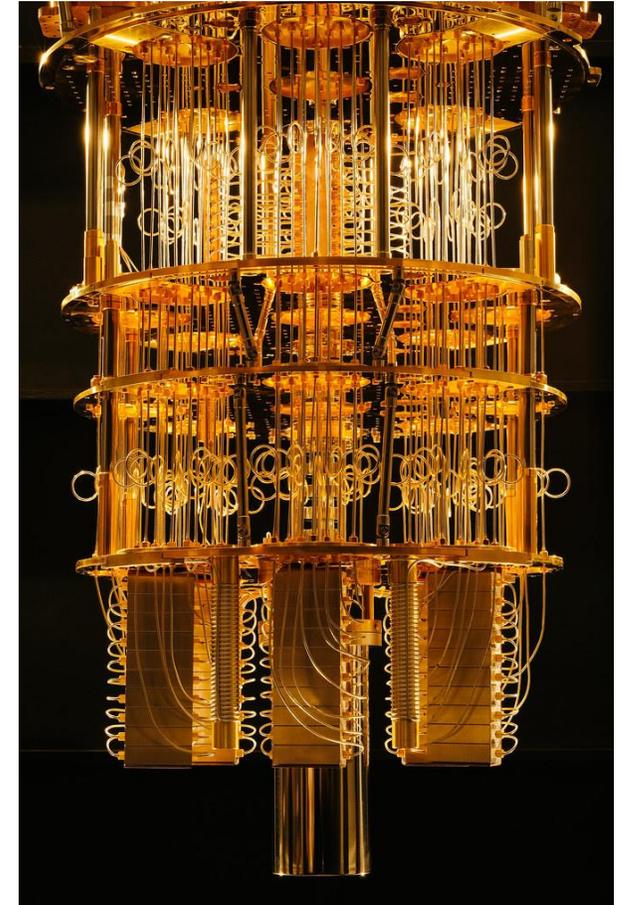
- Quantum communication takes advantage of superposition and entanglement to **encode** and **transmit** information.
 - **Quantum Key Distribution (QKD)** is a protocol allowing two parties to share a **quantum encryption key** (entangled qubits). Any attempts to intercept the message disrupt the entangled qubits and becomes **manifest**.
- QKD could enable **secure communication in the post-quantum era**, i.e., when quantum computers will reach **crypto-analytical capabilities**.



Quantum computers

“How can we simulate quantum mechanics? Can you do it with a new kind of computer – a **quantum computer**? Not a Turing machine, but a machine of a **different kind**.”
([Feynman 1982](#))

- Traditional computers process bits sequentially (0 **or** 1).
- In QC, bits (called **qubits**) are superposed, meaning that they can assume, simultaneously, two states (0 **and** 1), thus **boosting computation**.



"IBM quantum computer" by [IBM Research](#) is licensed under [CC BY-ND 2.0](#).



Unpacking the book



Three technological ecologies of sens-making

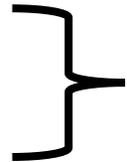
- Tech as a “**dispositif**” ([Agamben 2009](#)) that shapes a certain grasping of information, that is, a systemic sensing of reality.

“Sens” as:

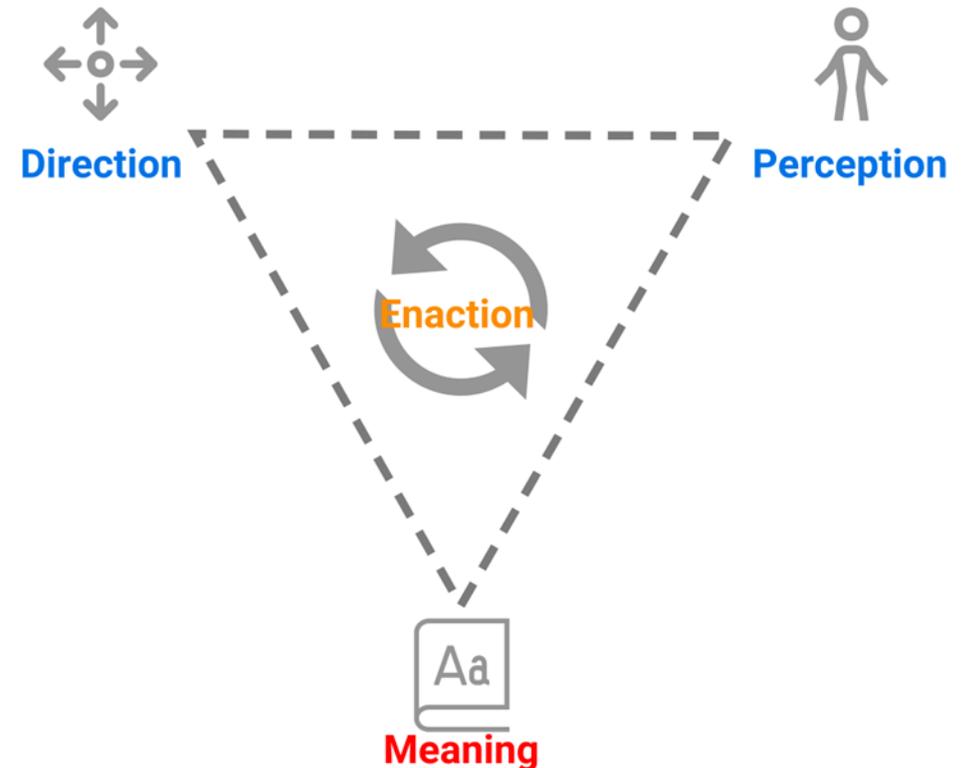
- **Direction**

- **Perception**

- **Meaning**: frames the other two as “a (**sixth**) **sense modality** for ‘perceiving’ psychophysical correlations.” ([Atmanspacher 2020](#))



They depend on a certain positioning in the world



Three ecologies

1) Language → based on **meaningful world-sensing** (e.g., alphabetic & logographic writings).



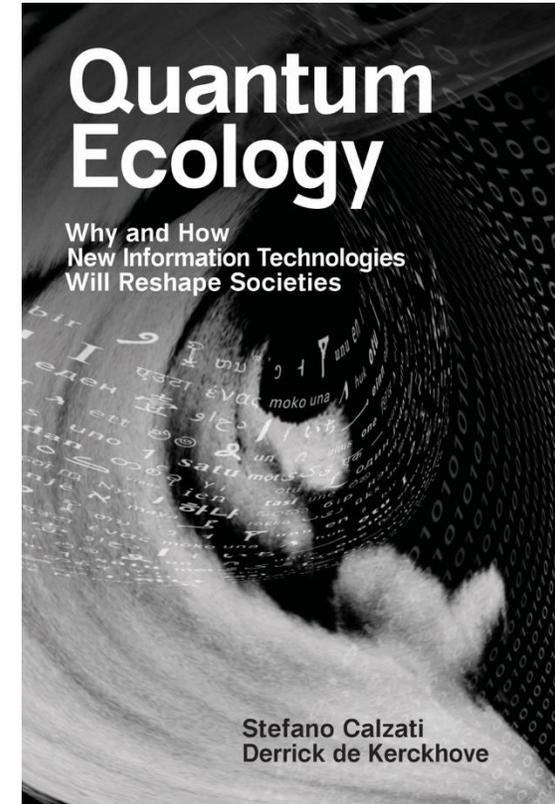
Partial onto-epistemological
incommensurability
(LLMs are here!)

2) Digital → based on **computable world-sensing** (formatting of sensing into 0s & 1s).



Partial onto-epistemological
incommensurability

3) Quantum → based on a **probabilistic world-sensing** (synthetic sensing).



“An ecology has effects, but not causes, at least not causes in the ordinary sense of a direct cause-effect relationship.”



(Embodied) language ecology

Language is a technology of the mouth as much as tools are technologies of the hands.
([Leroi-Gourhan 1965](#))

→ “Language as a co-ontogeny. With language arises the observer as a languaging entity.”
([Maturana & Varela 1987](#))

→ bio-linguistic world-sensing as “unprestatable”
([Kauffmann 2019](#))



"Altzerri. Leroi-Gourhan. Barandiaran ta abar" by Jesus Elosegi Irazusta is licensed under [CC BY-SA 4.0](#).

Linguistic metaphors



Metaphors as **Gordian knots** expressing abstract ideas via embodiment.

Time & space metaphors ([Boroditski 2010](#)):

- English speakers visualise the past at the back and the future in front
- Chinese speakers are **more flexible**: they can face the past; they can also enact time as above (past) and below (future)

→ Implications: if the link before-after is not an objective universal but a **socio-linguistically embodied construct**, then causality becomes situated, depending on **how people sense “facts”**.



Expressing quantum through language

“Schrödinger, Bohr, and Heisenberg spent so much time talking about **why any attempt to describe quantum concepts in language was likely to end in failure.**” ([Burwell 2018](#))

→ From what quantum phenomena “**mean**” to “**shut up and calculate!**”



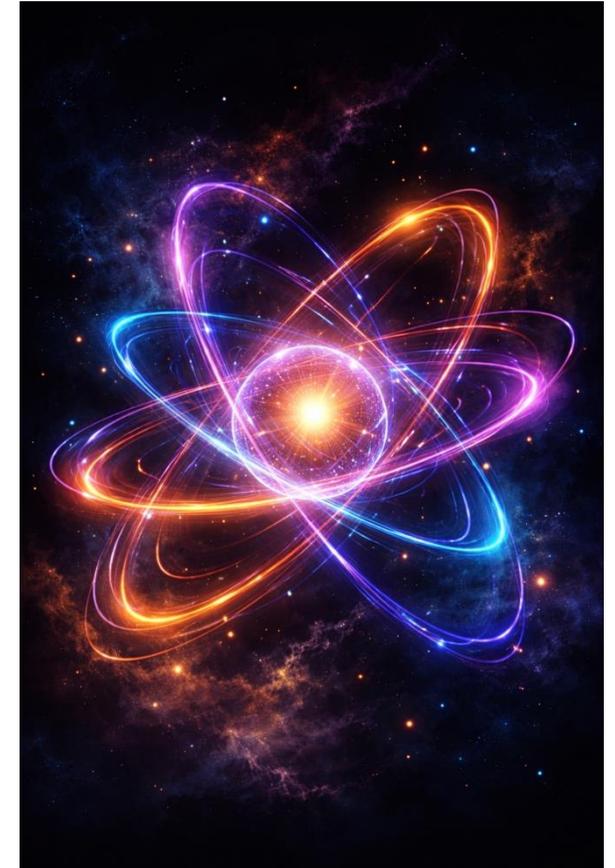
To spin or not to spin

Particles' spin is not really a spin, but a **linguistic proxy**.

- The idea of spin was introduced to describe a fourth degree of freedom of the electron (beyond the three-space dimensions), which Pauli defined as something “**which cannot be described from the classical point of view.**”

→ Language always provides a **certain** expression of the experience of the world...

...but this also applies to **mathematics!**

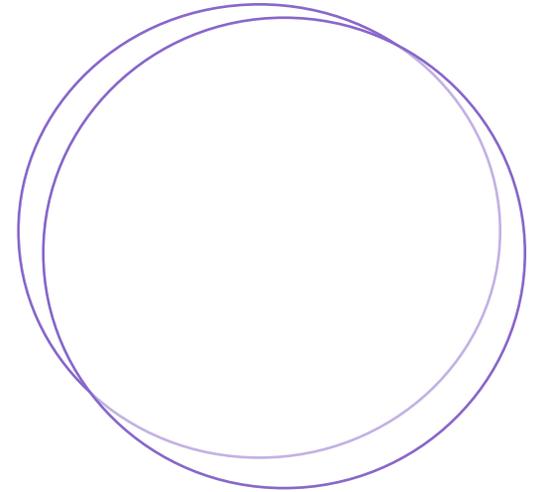


On the limits of mapping territories

“Ordinary language is a map which has a certain flexibility so that it can follow the curved shape of the territory” In math “**the relation of the symbols to our experience is no longer evident.**” ([Capra 1976](#))

“While the number avoids meaning something, **it cannot refrain from being significant**, establishing a relation with the world.” ([Agamben 2025](#))

→ Language and math configure **complementary “fictionalisations”** (etymology: “models”) of “reality”.



Digital ecology

- **Principle:** binary formatting of the sensible
- **Driving logic:** sheer efficiency
- **Effects:** global networkedness

→ The digital transformation has brought forth a computability transition that challenges **bio-linguistic world-sensing**.



Implications

Pervasive computing “**envelops**” reality into an efficient scenario.
([Floridi 2019](#))

Envelopment fits **computational agents** but less so **biological ones**.

→ implosion of the “rational subject” as a proxy: human agents as **inherently inconsistent** (behavioural ethics; cf. [Pink et al 2024](#)), i.e., **holding superposed values at once** (and complementary views)



Ideas for applying the quantum ecology as a framework



Quantum-inspired policymaking

- The philosophical tenets of quantum mechanics can inform **innovative ways of designing policy**:
 - **Operationalisation** of quantum principles and phenomena – e.g., uncertainty, superposition, entanglement, non-locality, complementarity – **for/through policymaking**.
 - **Overcoming linear extrapolations** (e.g., cause-effect links, cost-benefit analyses) and **deterministic decision-making**.



Emerging ideas

“Policymakers must account for a range of **potential futures**. **Policy impacts are entangled** and require constant observation, guided by multi-criteria analysis and trade-off assessments.” ([Renda 2025](#))

“Leveraging a new perspective on **uncertainty offers a sophisticated framework for decision-making** in the face of the many uncertainties of quantum and other technologies.” ([Meckel et al 2025](#))

“Incorporating concepts like **superposition** (multiple simultaneous stakeholder preferences), **entanglement** (interconnected policy dynamics across sectors), and **interference effects** (unexpected shifts in preferences) (...) helps navigate complex policy environments” based on **quantum probability**. ([Myeong et al 2025](#))



(Possible) ways forward

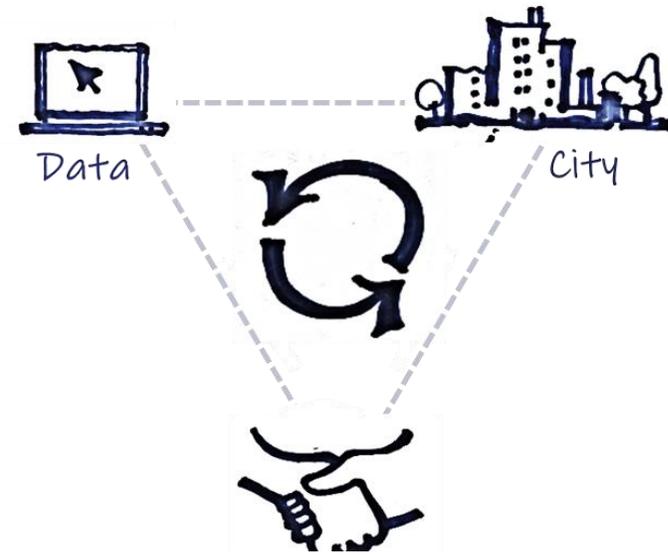
- 1) How can we **shape adaptive policymaking** that revolves around **fundamental uncertainty** and **systemic entanglement** (e.g. beyond ex-ante risk-based approaches)?
- 2) How can we **design policy** in such a way as to accommodate **complementary scenarios** and effects (e.g., **nonlocal trade-offs**)?
- 3) How do **value-based behavioural superpositions** can be embedded in **complexity-informed policymaking** (e.g., beyond the rational subject)?



Ethics for the data driven-city (Calzati & Ploeger 2024)

Pillars:

- Data as **sociotechnical bundlings**.
- Ethics as a **collective ongoing practice**.
- City as a **complex system**.



Problem-opening approach



“Technology is neither good nor bad; **nor is it neutral.**”
([Kranzberg 1985](#))

Technology as “**pharmakon**” (at once, good and bad;
both poison **and** antidote).

→ its use in complex scenarios produce **value-laden entanglements** (good and bad) and **uncertain consequences** (intended and unintended).

Research & design

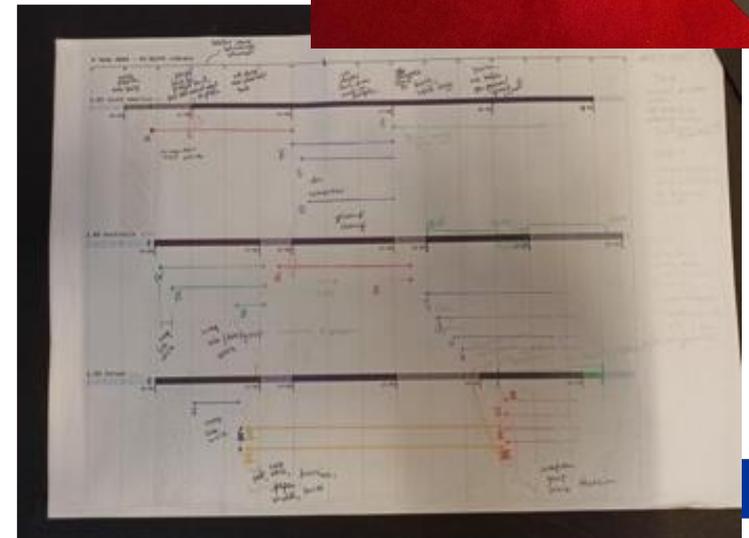
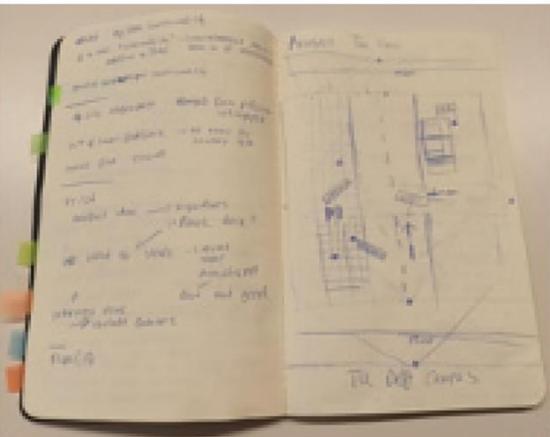
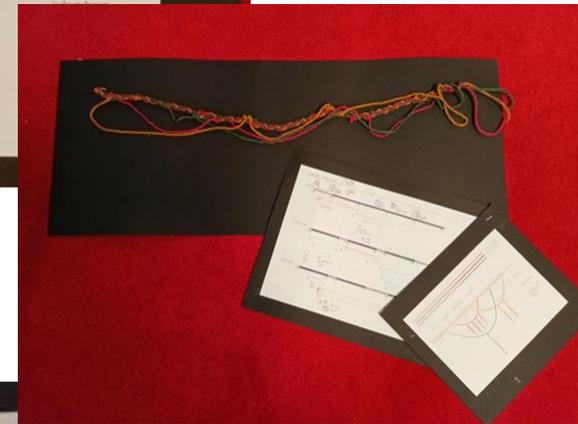
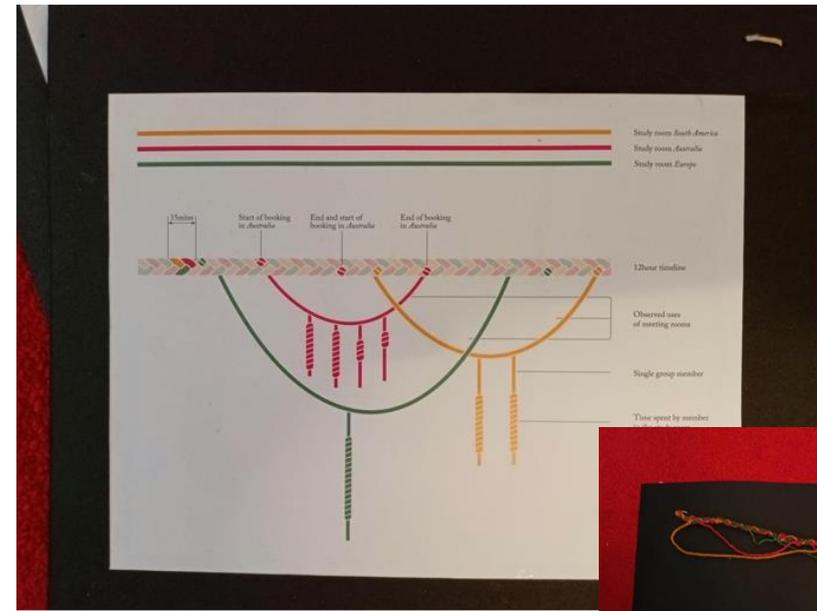
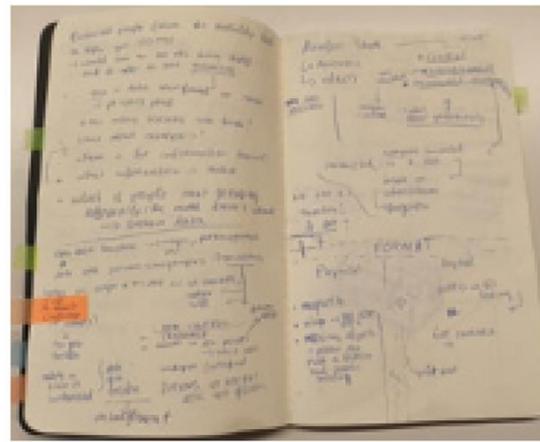
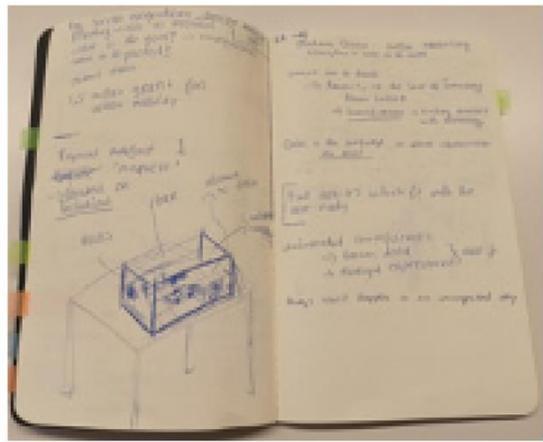
Research

- 1) **Identification** of a case study.
- 2) **Framing** of the case study (e.g., how it is presented; how it works; etc.).
- 3) **Data-value entanglements** (e.g., values in/excluded; data in/excluded).
- 4) **Open-ended scenarios** (e.g., possible un/intended consequences).

Design

- a) **Project journal**.
- b) **Artefact** (e.g., physical/digital object exposing/redressing the tensions identified).
- c) **Author's statement** describing the artefact.





“Design is **indeterminate** in order to be practical” ([Easterling 2021](#))



Insights into the quantum ecology as a technological paradigm



QITs as a “wicked” policy issue

To be labelled “**wicked**”, a policy issue must have **complexity, uncertainty, and disagreement**. ([Head 2022](#))

Two wicked **QITs policy issues** ([Moloney & Al-Kuwari 2025](#)):

- 1) quantum techs impact on cybersecurity.
- 2) quantum techs impact across policy sectors.

→ Policy agenda-setters should include **economic values** (e.g., efficiency, economy) and **noneconomic public values** (e.g., fairness, transparency, trust, accountability, openness).

→ Key to policymaker action is quantum literacy, as the basis toward **quantum readiness** and **quantum-safe transition**.



Quantum-ready & quantum-safe transition

Challenges for public sector quantum-ready & quantum-safe transition ([Kong et al 2024](#)):

- **Technical** (e.g., no QS fit-for-all solution).
- **Organisational** (e.g., perceived urgency, literacy, and in-house capabilities).
- **Ecosystemic** (e.g., guidance & coordination within and across public organisations).

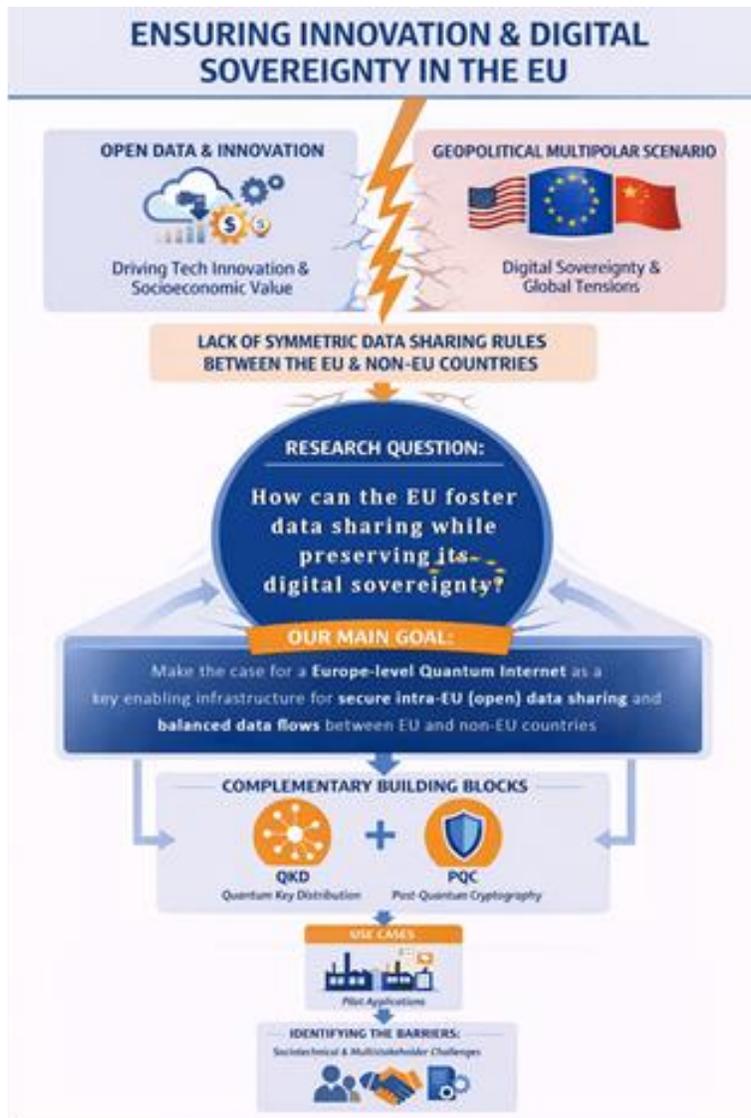
- 1) What's the current **JRC quantum-safe technical readiness** (e.g., against "harvest now decrypt later" threat)?
- 2) What are the barriers and enablers to make the JRC **quantum-ready at organisational and ecosystemic** levels?
- 3) Which policy information, roles, and processes are more sensitive to a quantum-safe transition, i.e., would benefit the most from a **JRC quantum-safe policy network**?



Safeguarding the EU data assets

- **Open Data** (OD) are pivotal to **technological innovation** and the creation of **socioeconomic value**.
- However, **OD face challenges within today's multipolar geopolitical scenario**, which has triggered digital sovereign positions across the globe.
- Currently, **we miss symmetric cross-border data sharing frameworks** between the EU and non-EU countries (e.g., US and China), requiring the EU to safeguard its OD.
- How can the EU **keep enacting (open) data sharing** that both fuels its internal tech innovation and creation of socioeconomic value, **while also preserving the EU's digital sovereignty outwardly?**





EU quantum internet

(Calzati, Nikofova, Travagnin, under review)

A **Europe-level Quantum Internet for the EU digital sovereignty** enabling secure intra-EU data sharing and balanced cross-border data flows.

Challenges are sociotechnical:

- multistakeholder cooperation across sectors to enable the **scaling of current quantum networks** and their **supra-national governance**.
- Multidisciplinary cooperation to **ensure the sustainability of a EU-level QI** (including the study and mitigation of tech-dependencies along the quantum supply chain).



Thank you!

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Quantum Ecology

Why and How
New Information Technologies
Will Reshape Societies

Stefano Calzati
Derrick de Kerckhove