Title: Representing time and time's arrow

Speakers: Bryan Roberts

Collection: Quantizing Time

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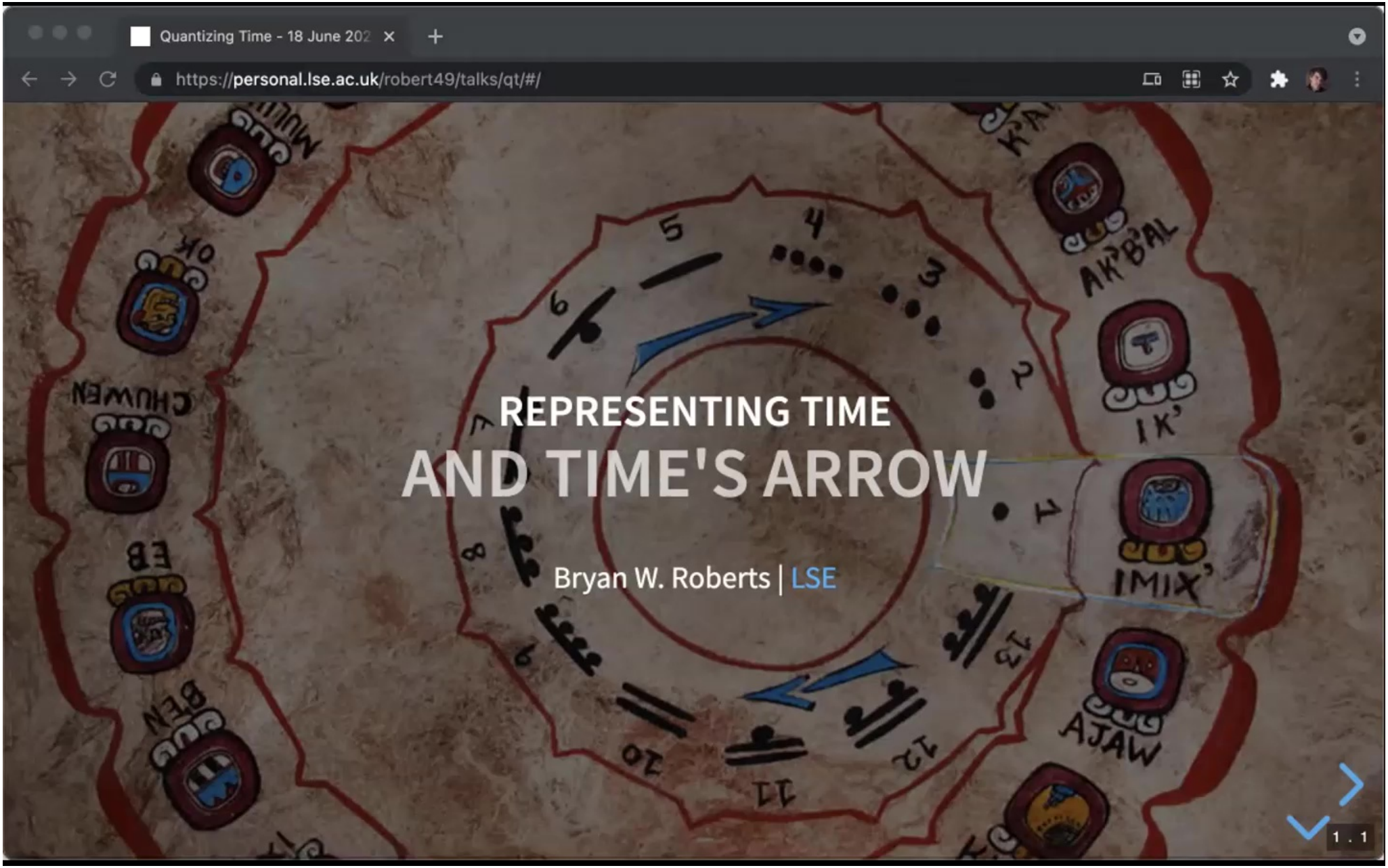
Abstract: What does it mean to say that a curve in state space describes change with respect to time, as opposed to space or any other parameter? What does it mean to say it's time is asymmetric? Inspired by the Wigner-Bargmann analysis of the PoincarÃ© group, I discuss a general framework for understanding the meaning of time evolution and temporal symmetry in terms of the representation of a semigroup that includes "time translations", amongst the automorphisms of a state space. I discuss the structuralist and functionalist philosophical underpinnings of this view, and show how time reversal, parity, matter-antimatter exchange, and CPT are best viewed as extensions of a representation of continuous symmetries, whose existence is sensitive to the underlying structure of state space. I conclude with some comments on how an arrow of time can be defined in this framework, as well as prospects for such an arrow in the context of gravitation.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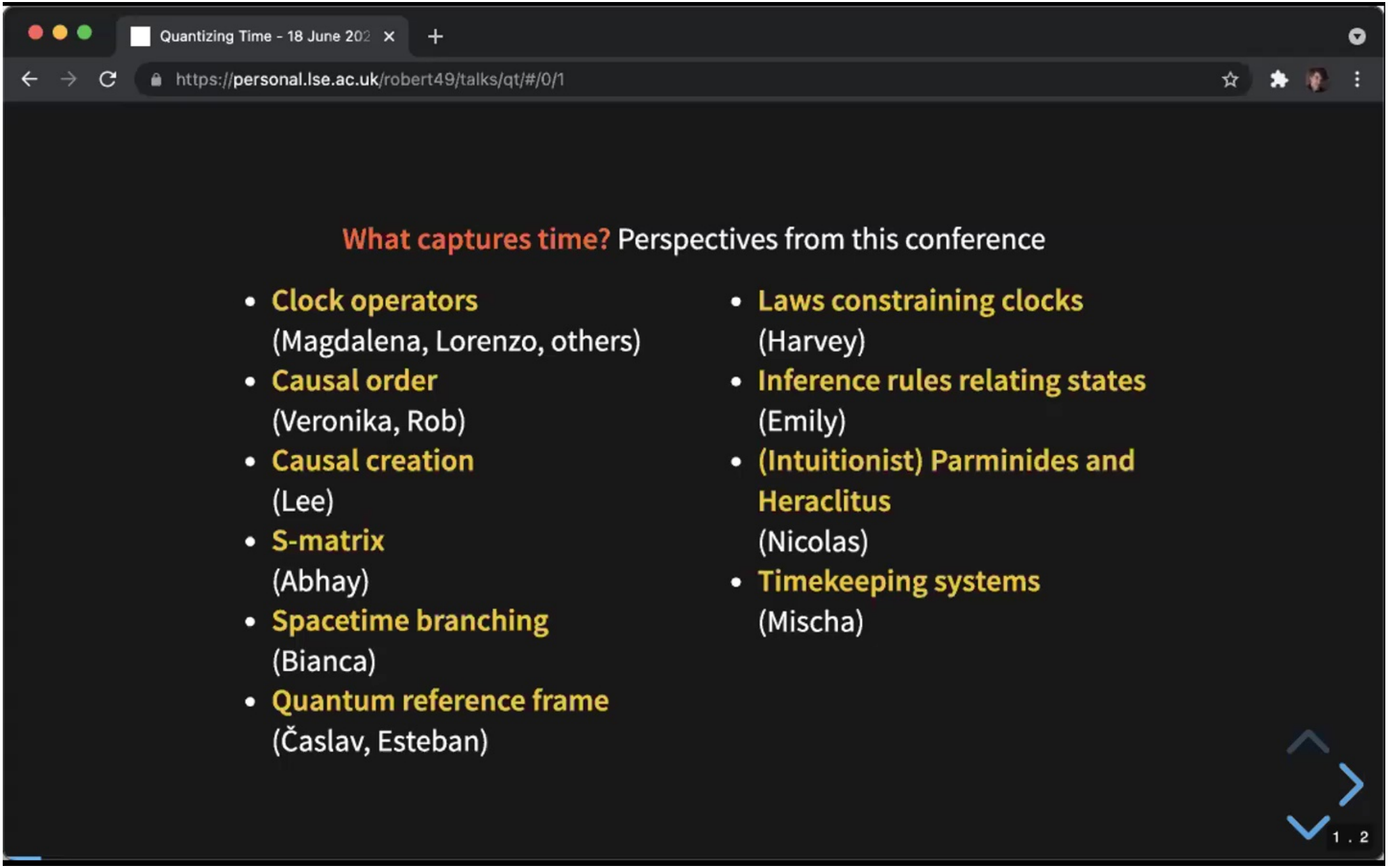
REPRESENTING TIME
AND TIME'S ARROW
Bryan W. Roberts | LSE
1 . 1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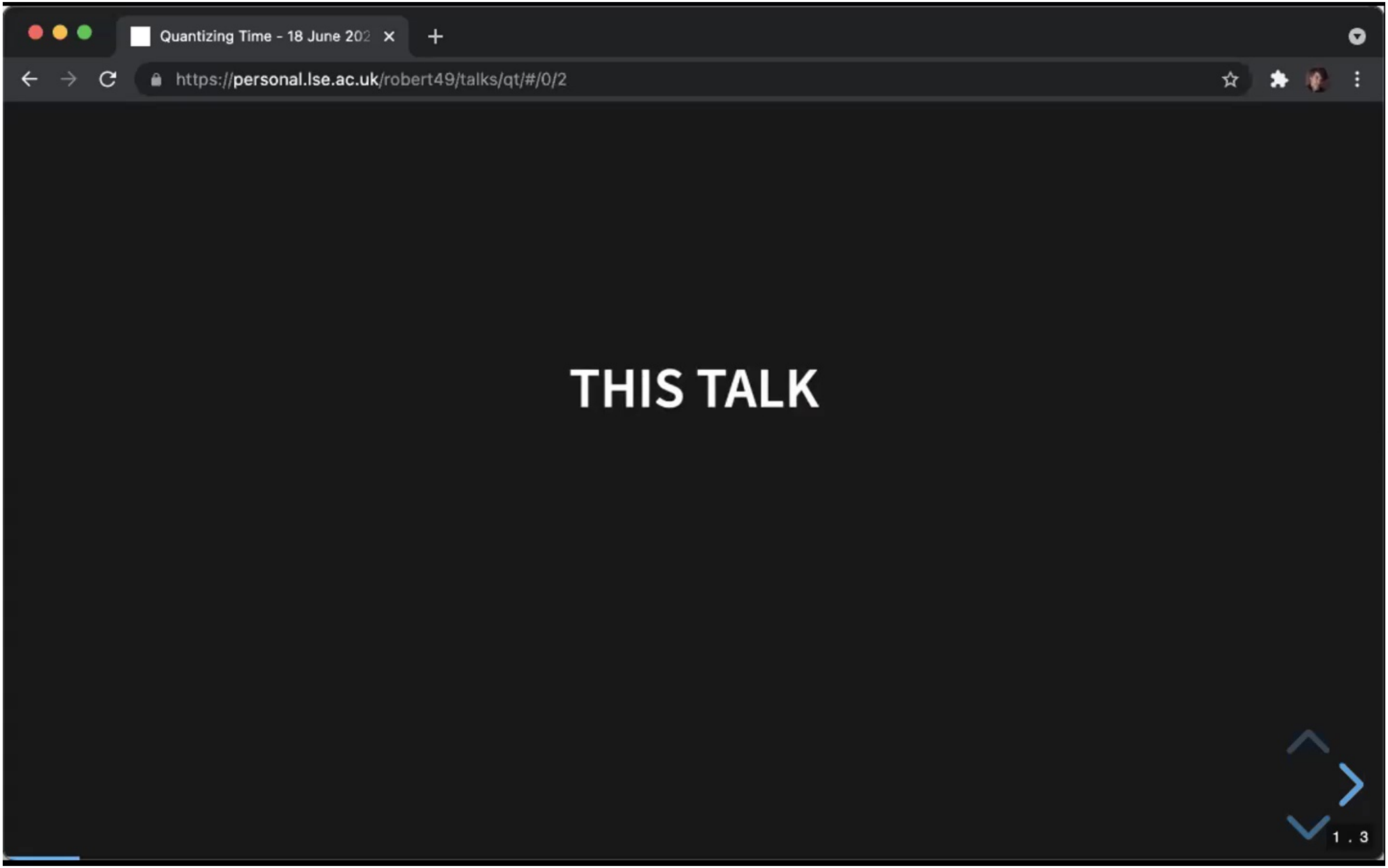
What captures time? Perspectives from this conference
Clock operators
(Magdalena, Lorenzo, others)
Causal order
(Veronika, Rob)
Causal creation
(Lee)
S-matrix
(Abhay)
Spacetime branching
(Bianca)
Quantum reference frame
(Časlav, Esteban)
Laws constraining clocks
(Harvey)
Inference rules relating states
(Emily)
(Intuitionist) Parminides and Heraclitus
(Nicolas)
Timekeeping systems
(Mischa)
1 . 2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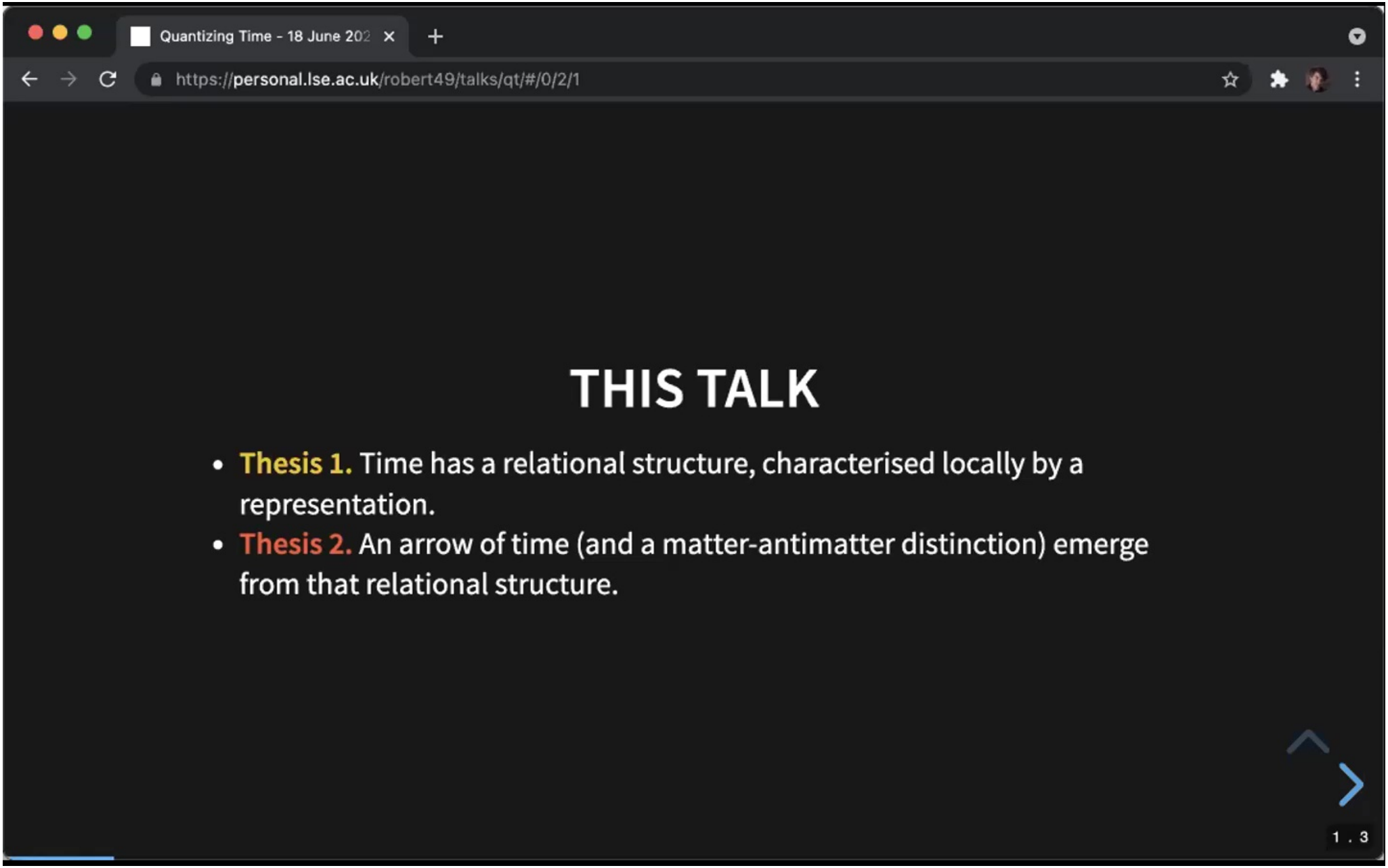
THIS TALK
1 . 3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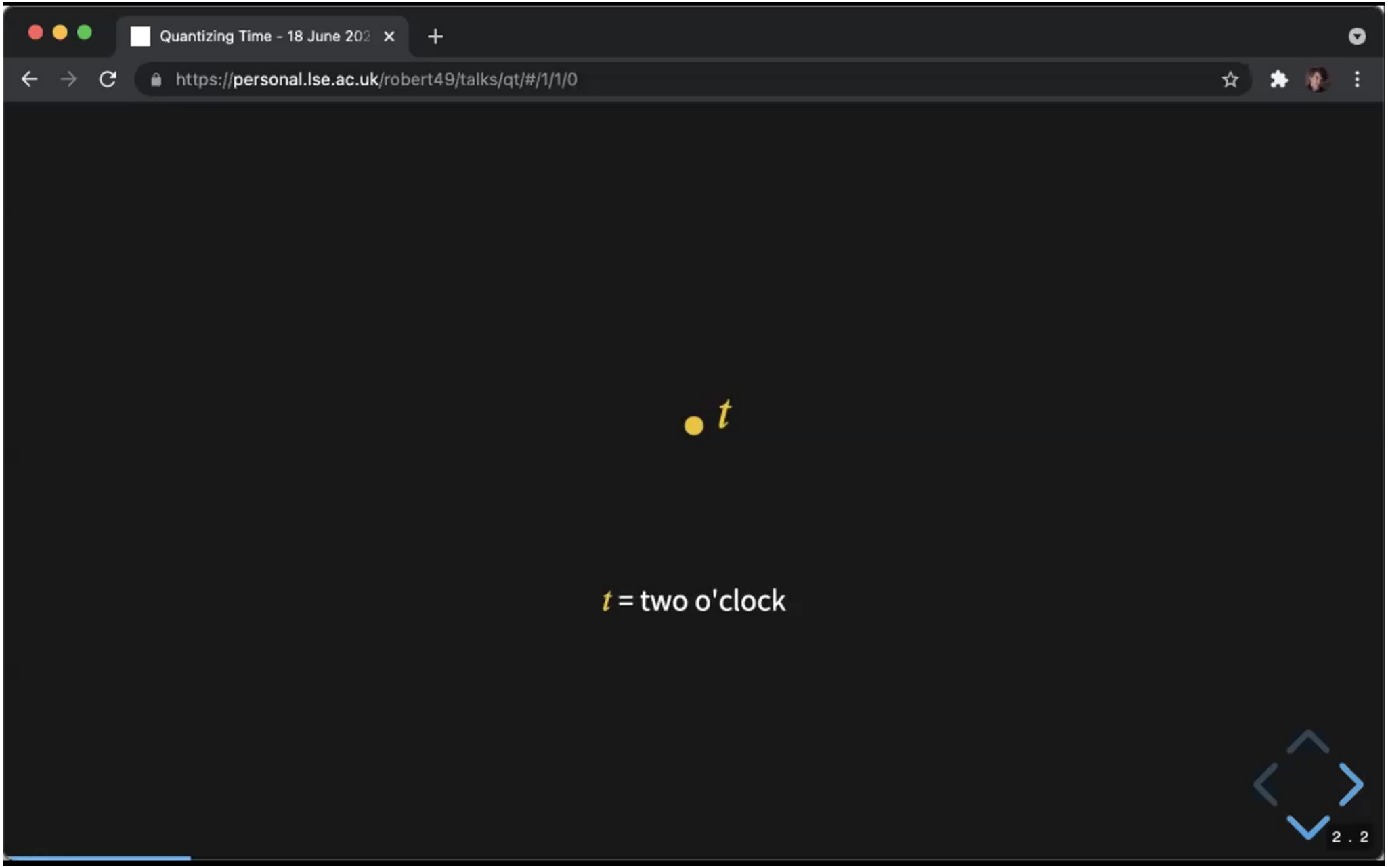
THIS TALK
Thesis 1. Time has a relational structure, characterised locally by a representation.
Thesis 2. An arrow of time (and a matter-antimatter distinction) emerge from that relational structure.
1 . 3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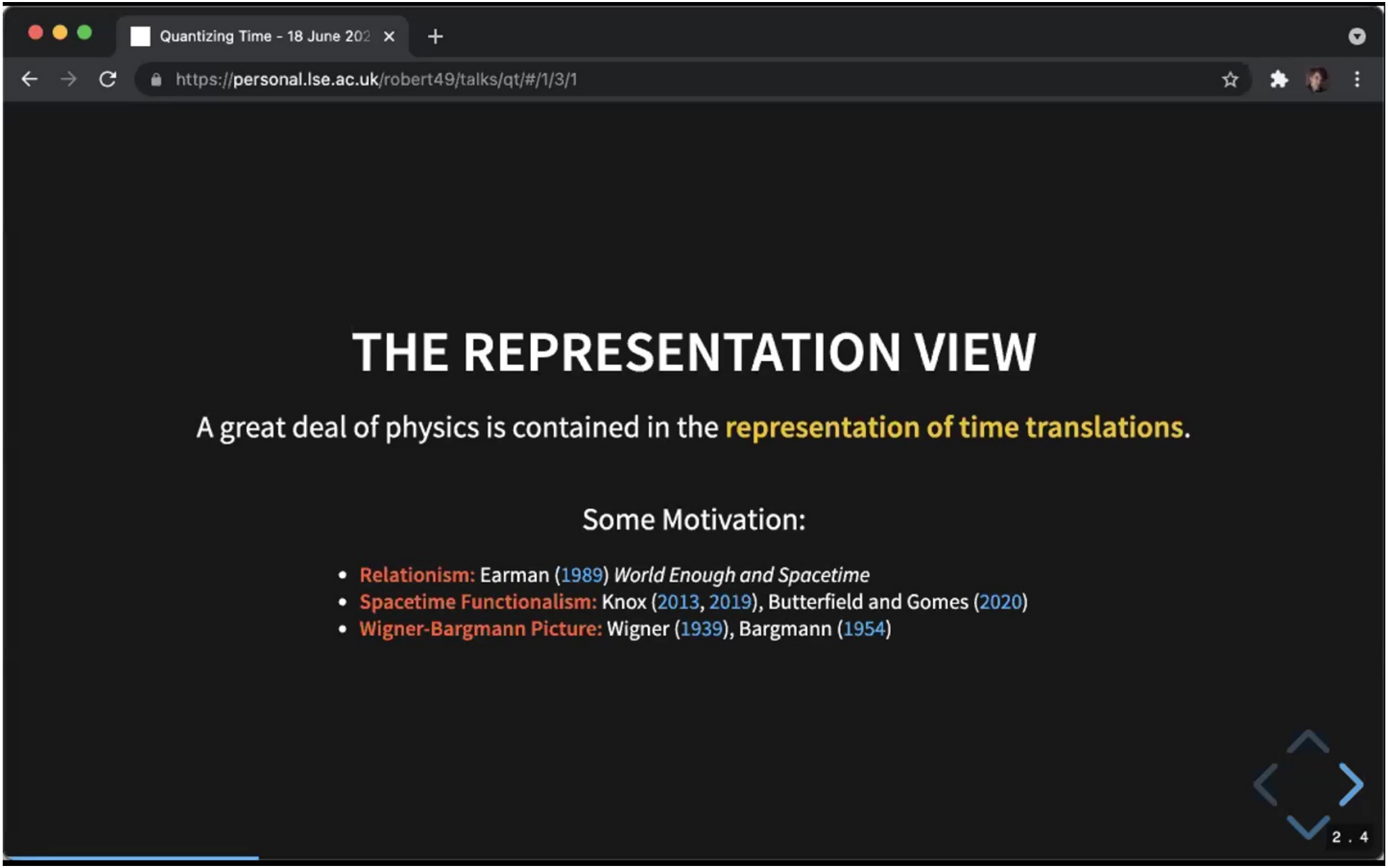
t
t = two o'clock
2 . 2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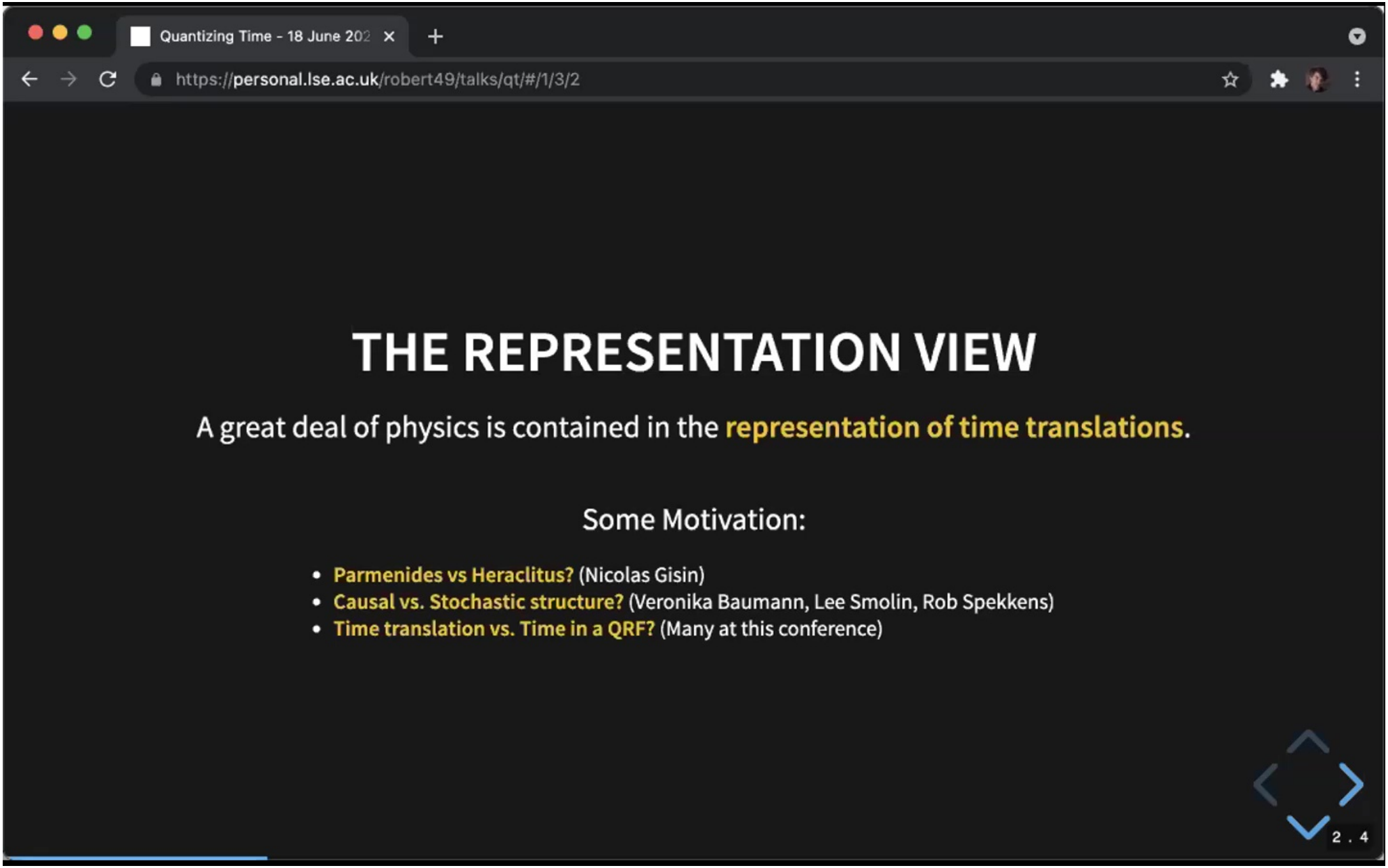
THE REPRESENTATION VIEW
A great deal of physics is contained in the representation of time translations.
Some Motivation:
Relationism: Earman (1989) World Enough and Spacetime
Spacetime Functionalism: Knox (2013, 2019), Butterfield and Gomes (2020)
Wigner-Bargmann Picture: Wigner (1939), Bargmann (1954)
2 . 4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THE REPRESENTATION VIEW
A great deal of physics is contained in the representation of time translations.
Some Motivation:
Parmenides vs Heraclitus? (Nicolas Gisin)
Causal vs. Stochastic structure? (Veronika Baumann, Lee Smolin, Rob Spekkens)
Time translation vs. Time in a QRF? (Many at this conference)
2 . 4

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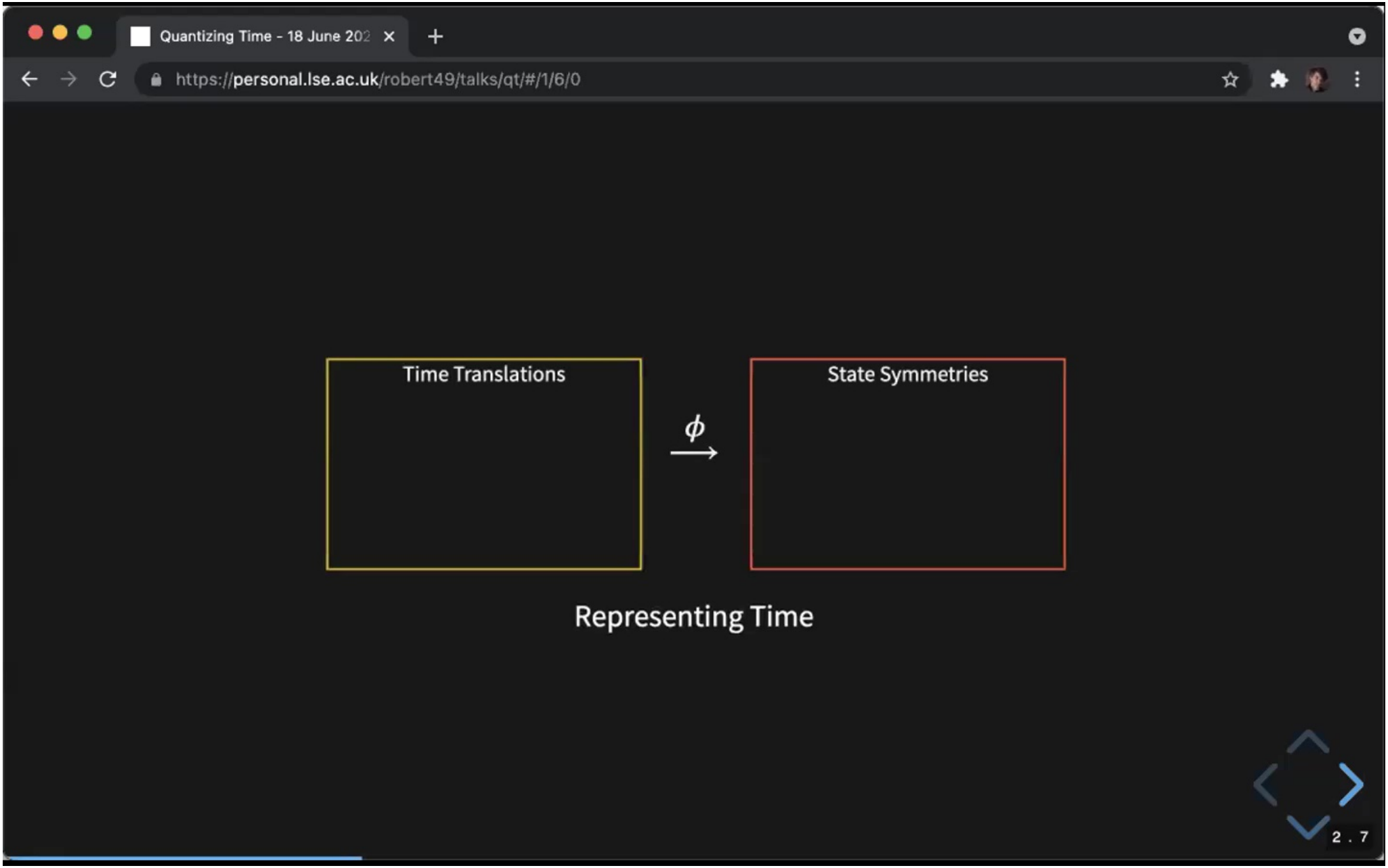
When do we have a **time translation** as opposed to a **spatial transation**?

- **Sociology:** When we use the letter *t*.

2 . 5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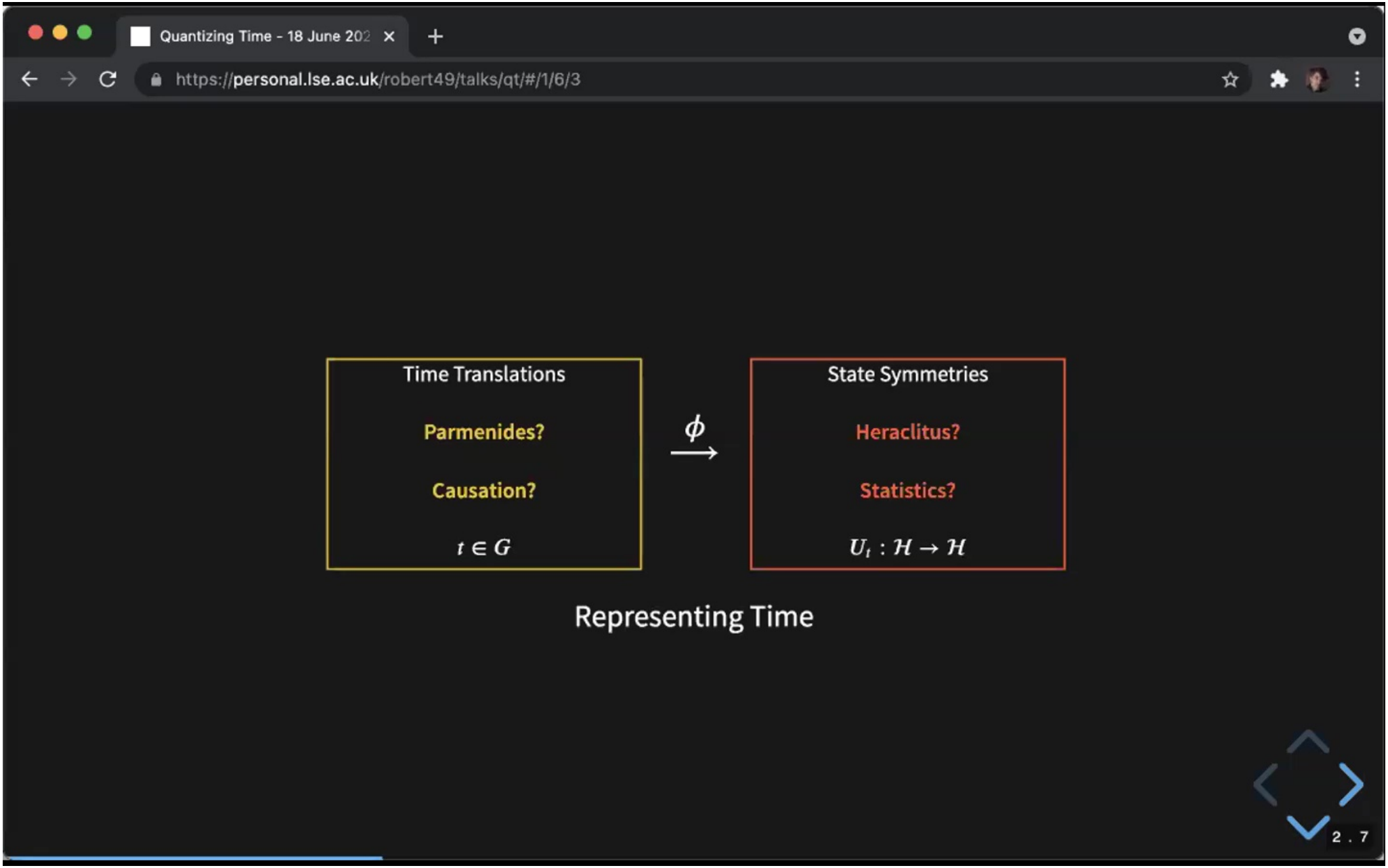
Time Translations
ϕ
State Symmetries
Representing Time
2 . 7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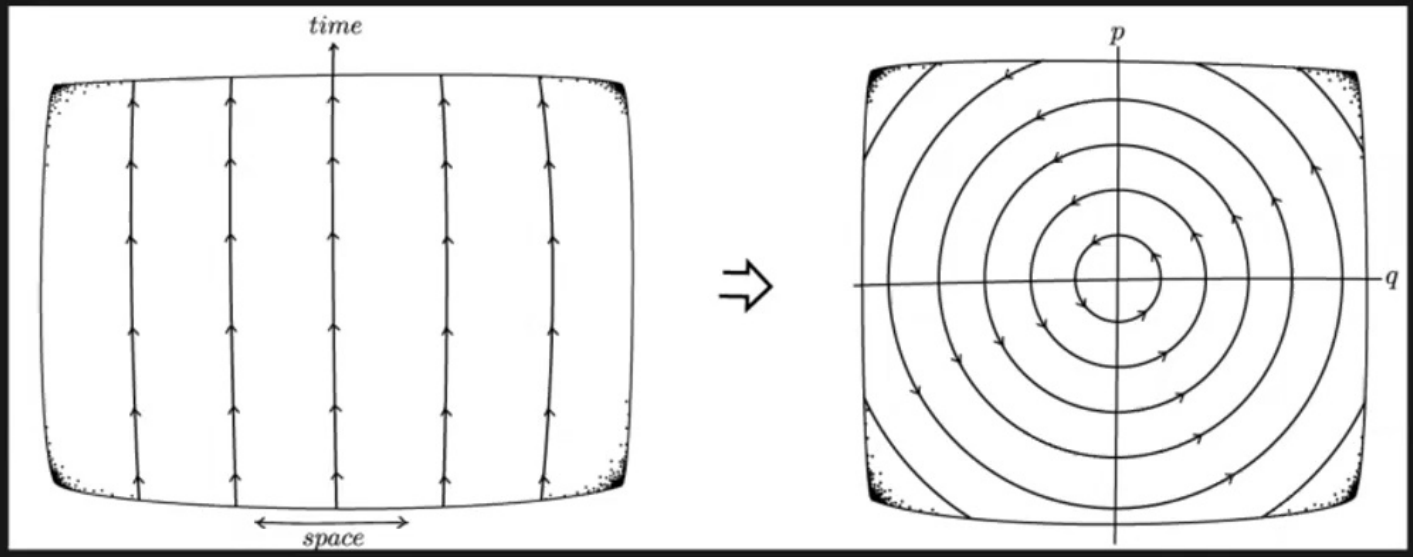
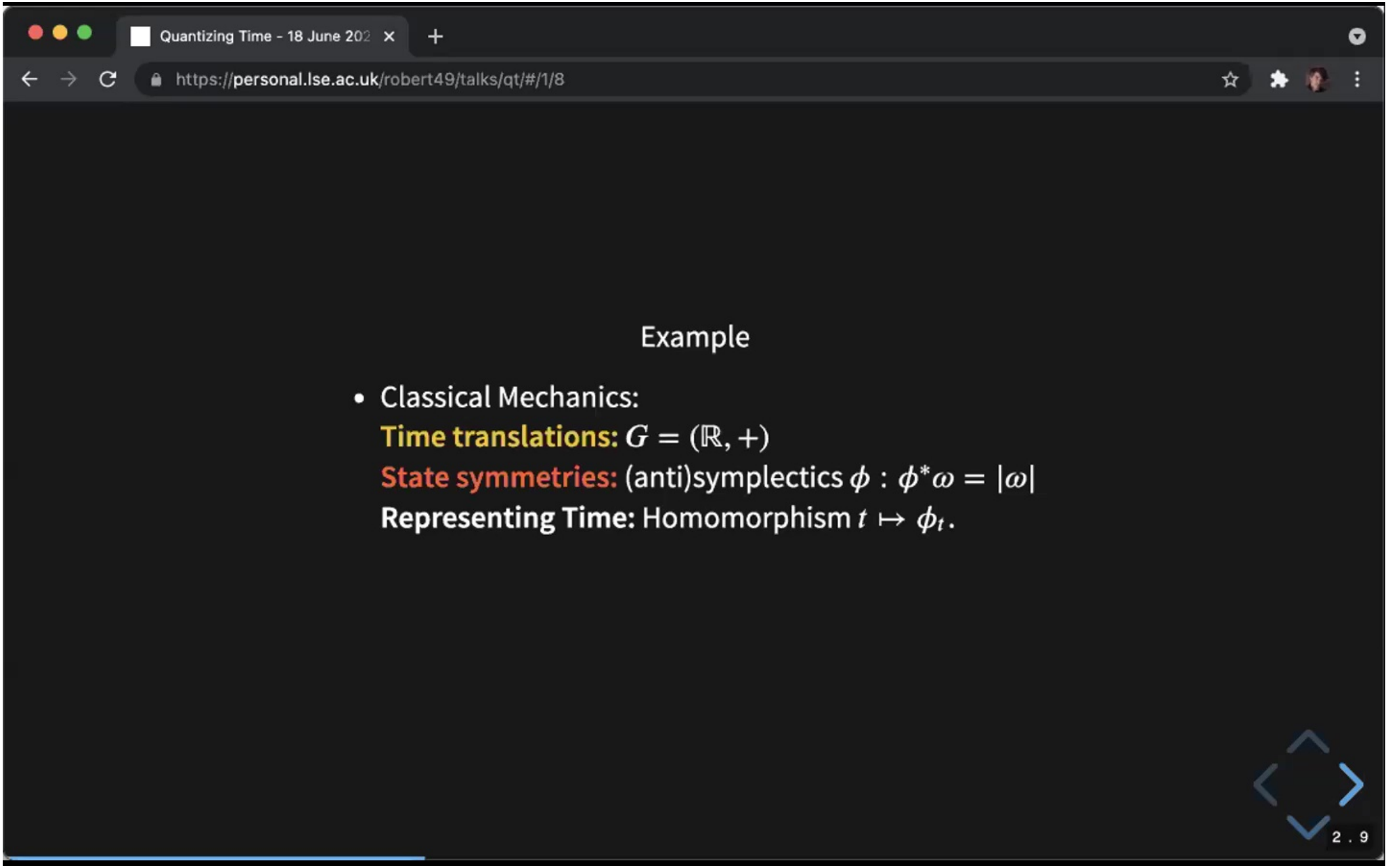
Time Translations
Parmenides?
Causation?
$t \in G$
ϕ
State Symmetries
Heraclitus?
Statistics?
$U_t : \mathcal{H} \to \mathcal{H}$
Representing Time
2 . 7

Example

Time translations represented among **State space symmetries**

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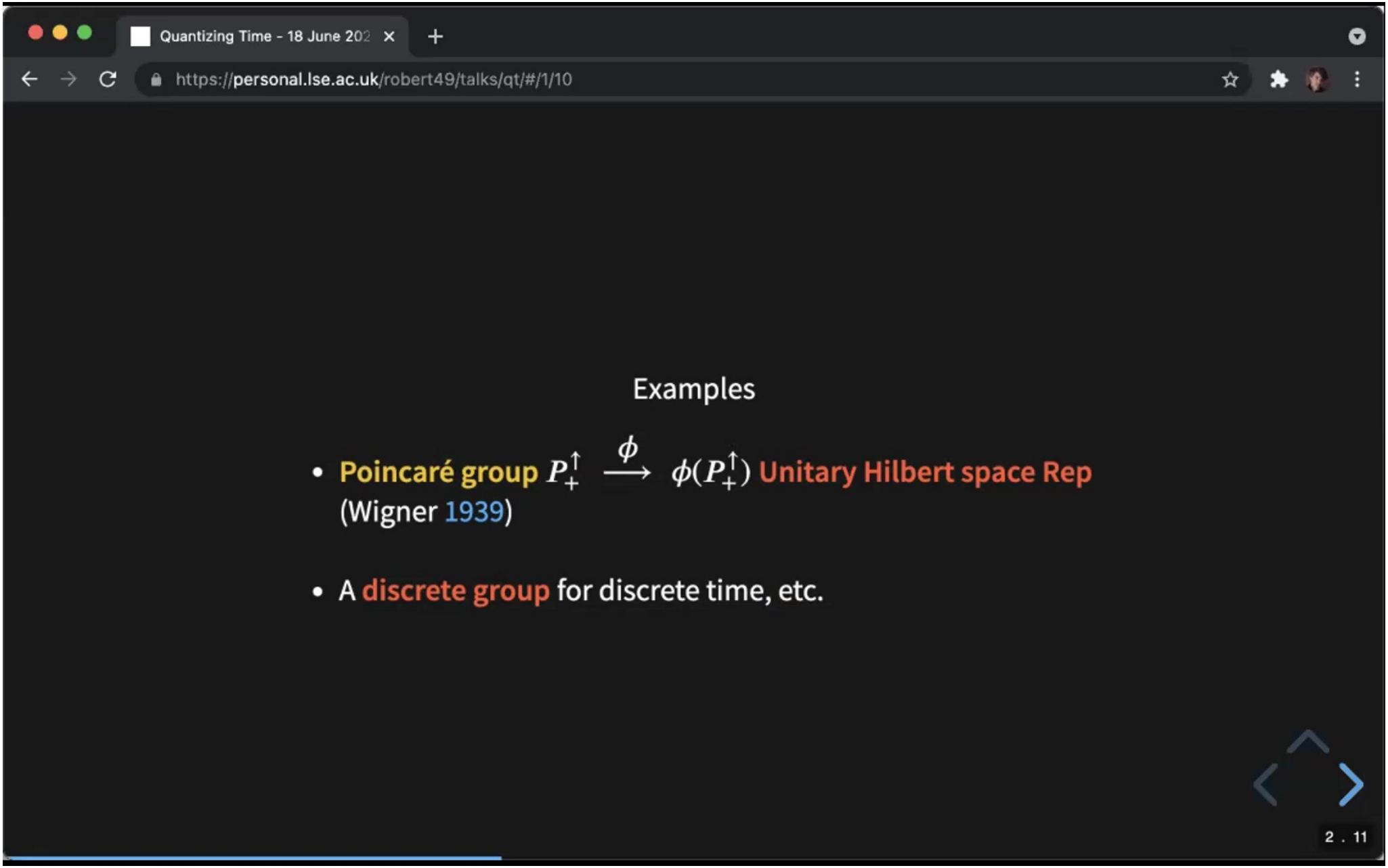
Example
Classical Mechanics:
Time translations: $G = (\mathbb{R}, +)$
State symmetries: (anti)symplectics $\phi : \phi^*\omega = |\omega|$
Representing Time: Homomorphism $t \mapsto \phi_t$.
2 . 9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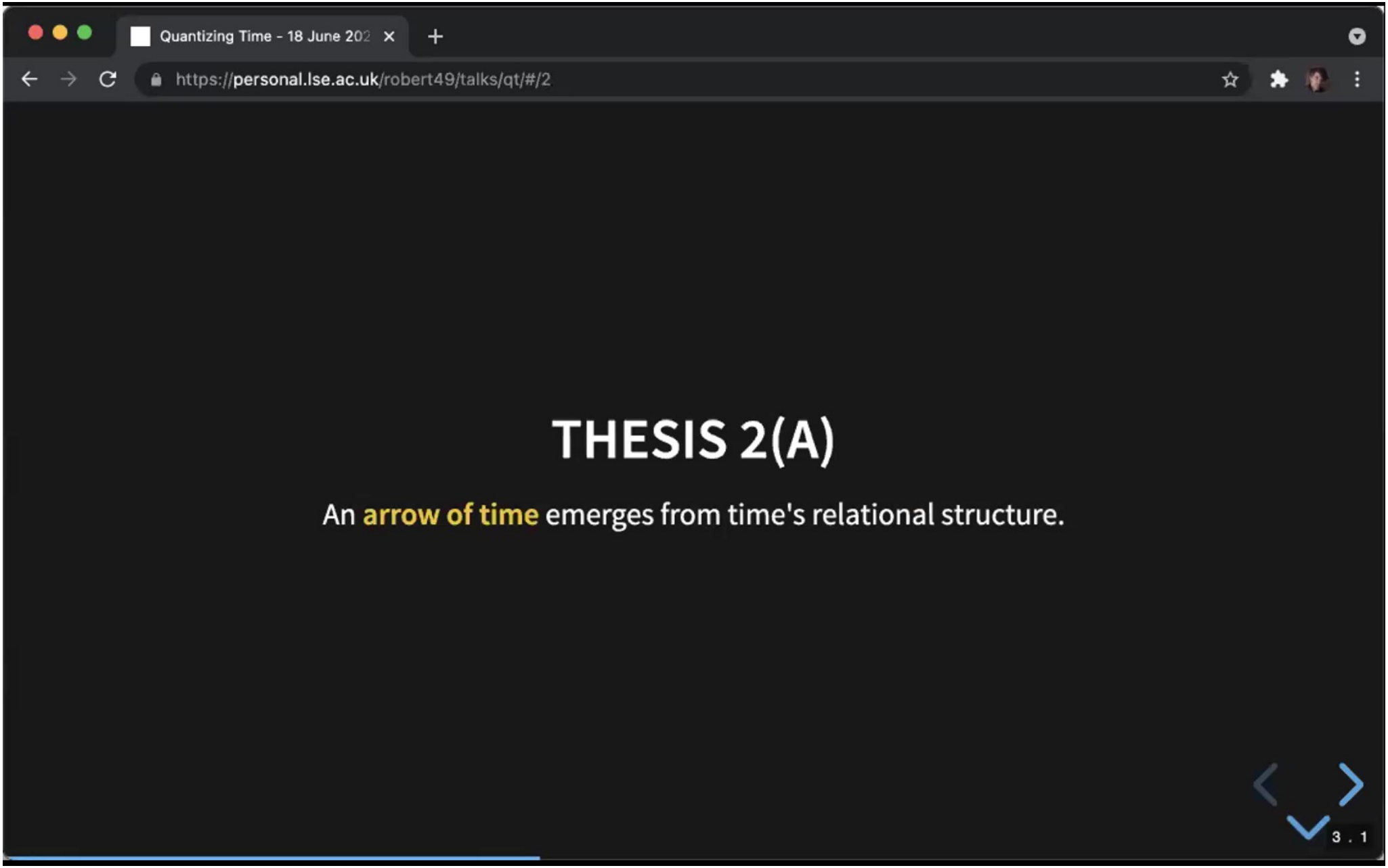
Examples
Poincaré group $P_+^\uparrow \xrightarrow{\phi} \phi(P_+^\uparrow)$ Unitary Hilbert space Rep
(Wigner 1939)
A discrete group for discrete time, etc.
2 . 11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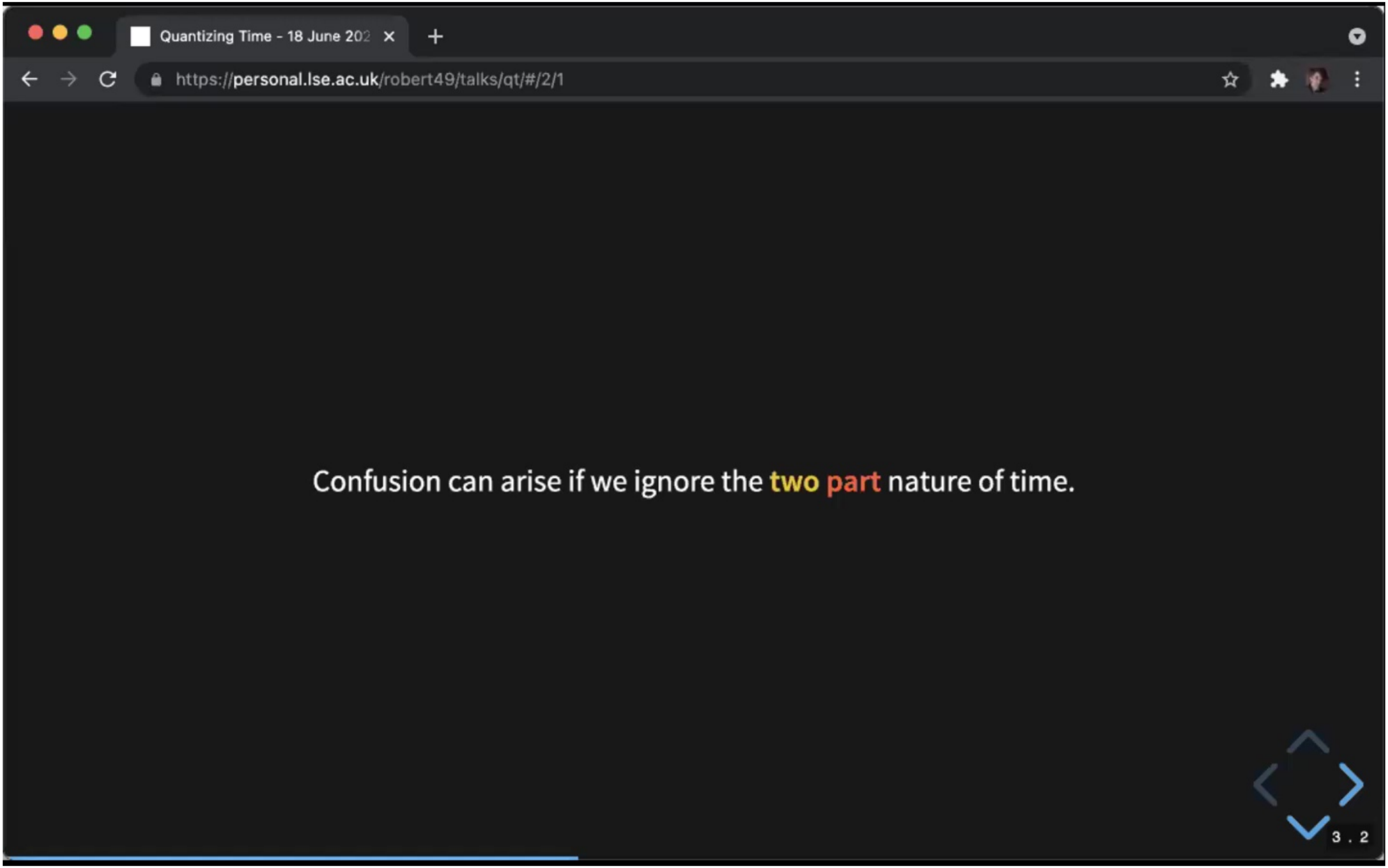
THESIS 2(A)
An arrow of time emerges from time's relational structure.
3 . 1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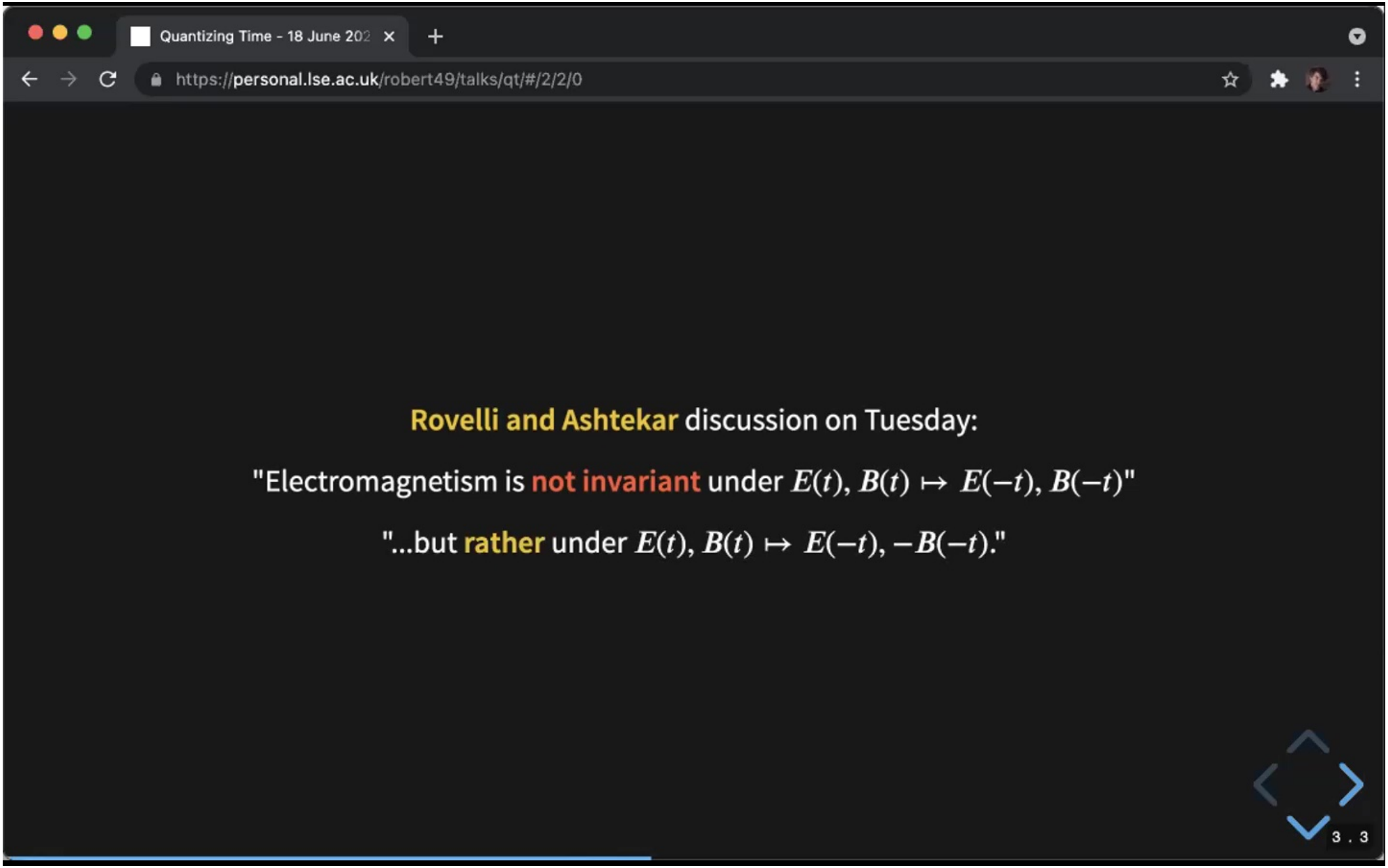
Confusion can arise if we ignore the two part nature of time.
3 . 2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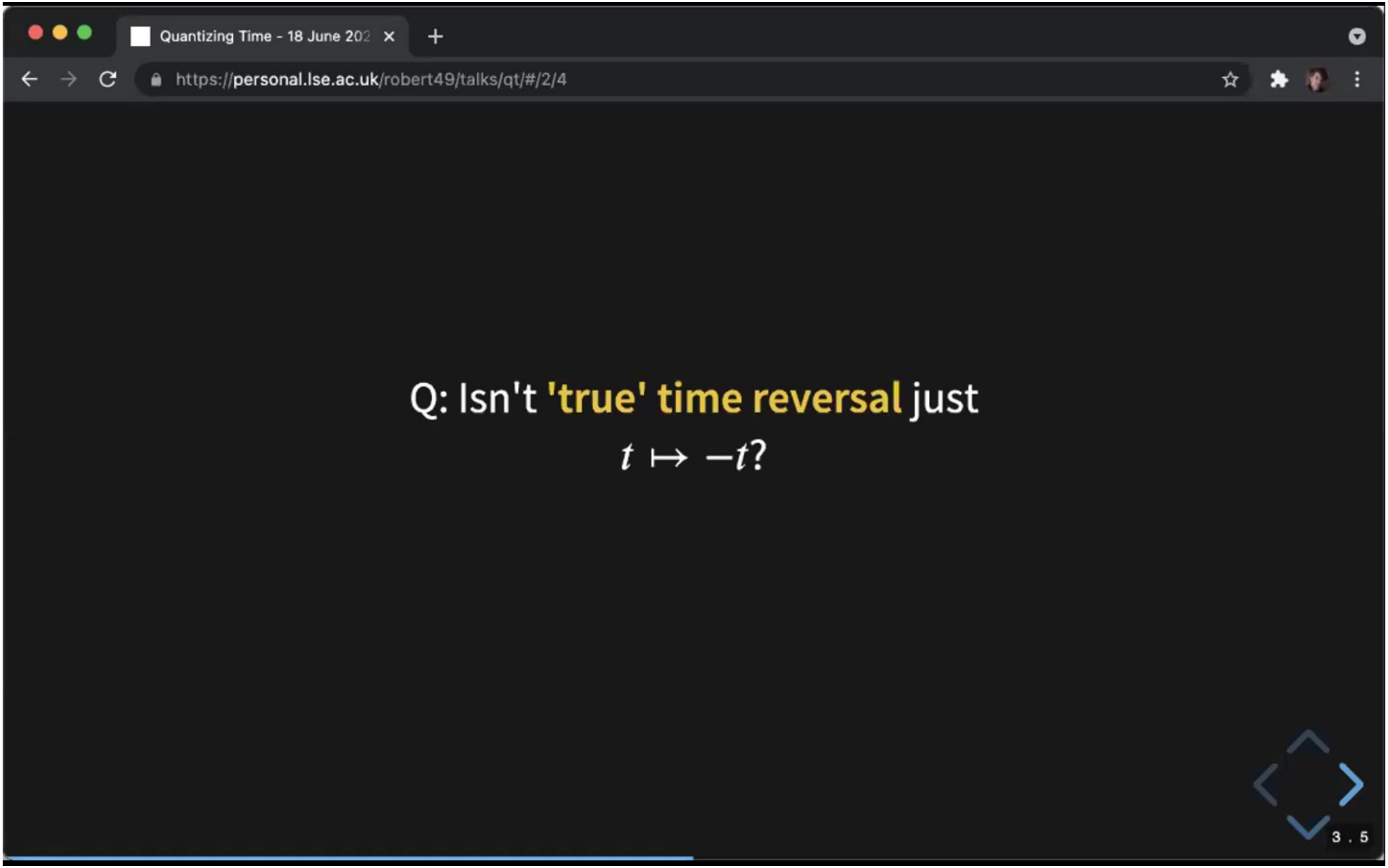
Rovelli and Ashtekar discussion on Tuesday:
"Electromagnetism is not invariant under $E(t), B(t) \mapsto E(-t), B(-t)$"
"...but rather under $E(t), B(t) \mapsto E(-t), -B(-t)$."
3 . 3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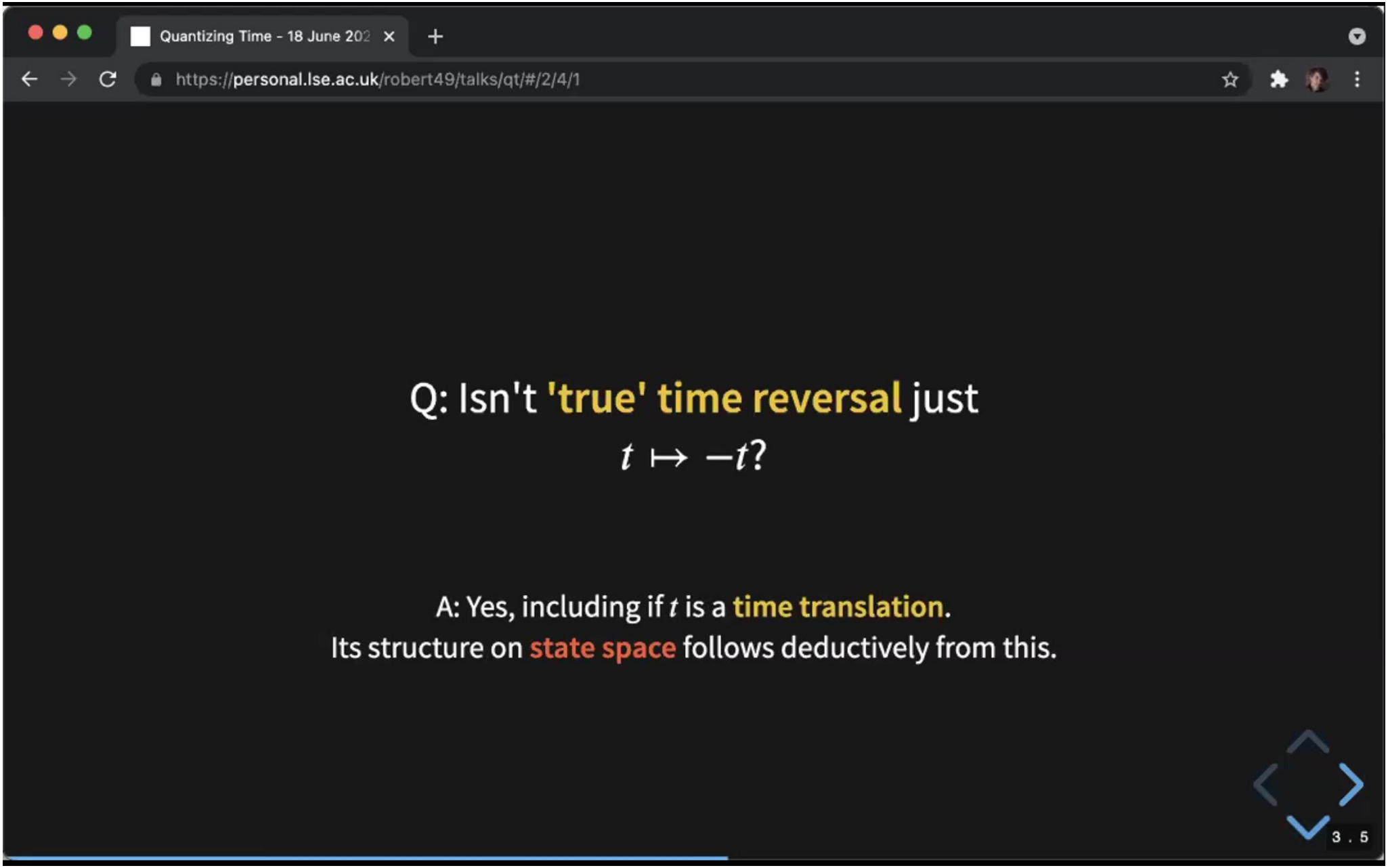
Q: Isn't 'true' time reversal just
$t \mapsto -t$?
3 . 5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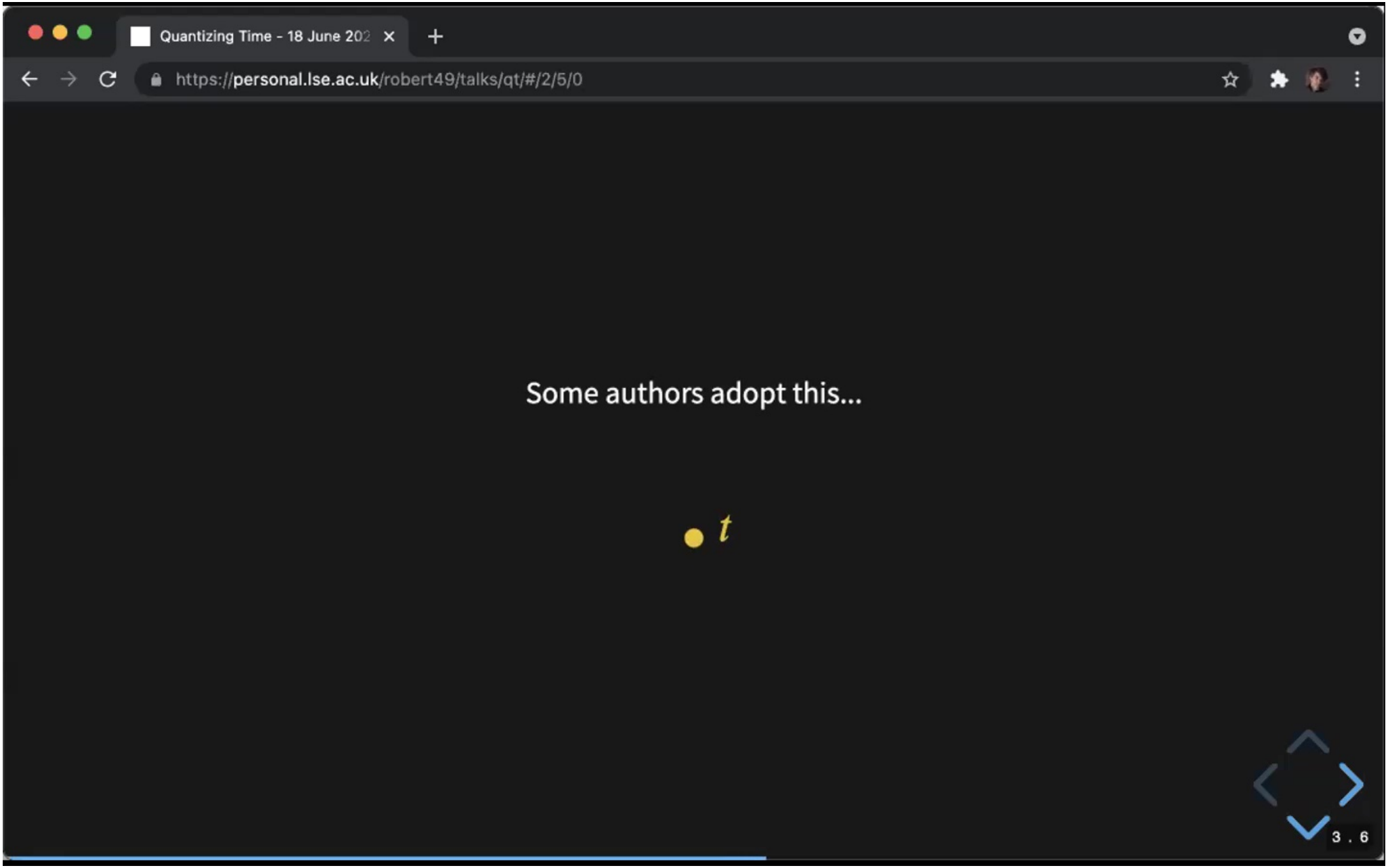
Q: Isn't 'true' time reversal just
$t \mapsto -t$?
A: Yes, including if t is a time translation.
Its structure on state space follows deductively from this.
3 . 5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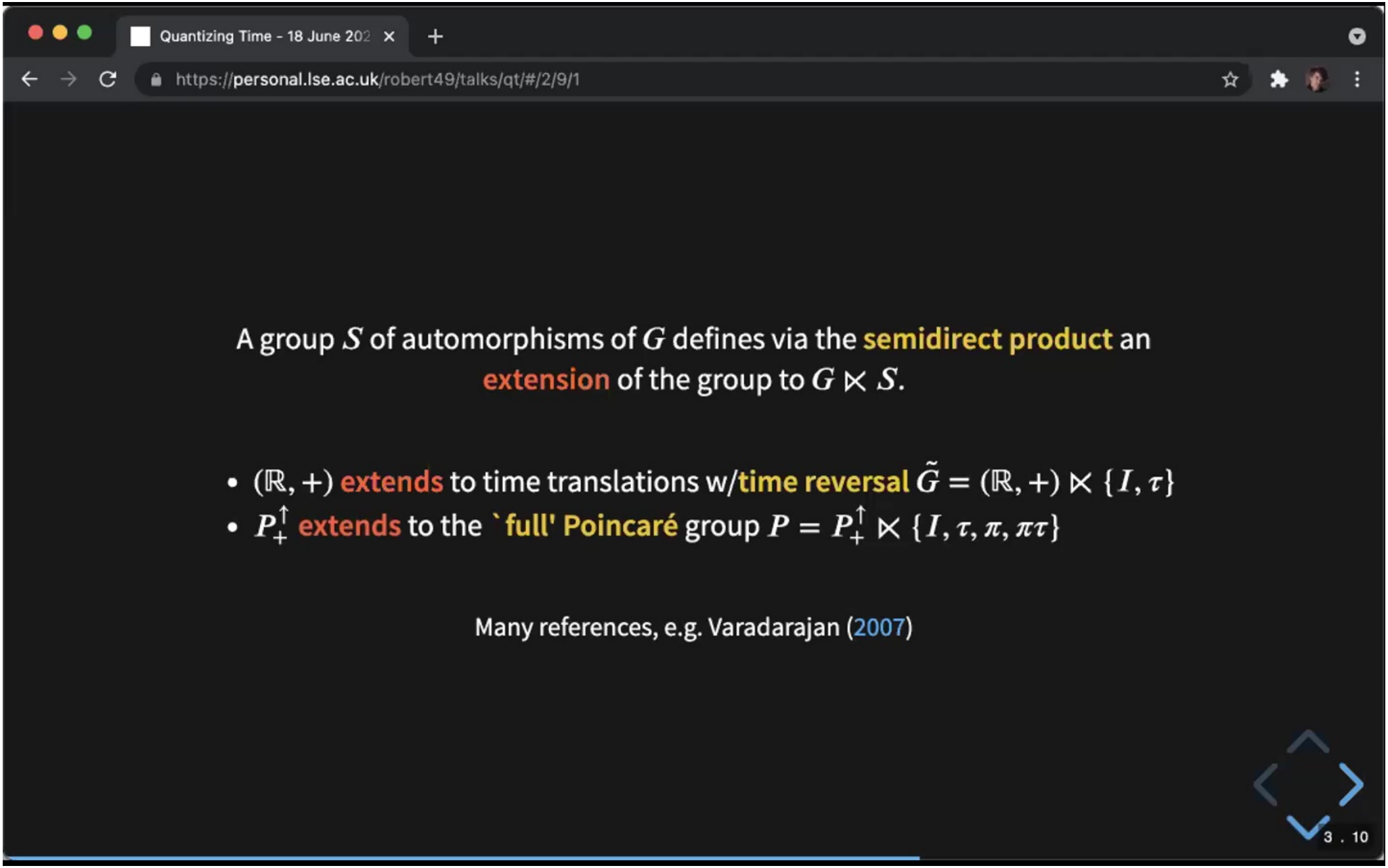
Some authors adopt this...
t
3 . 6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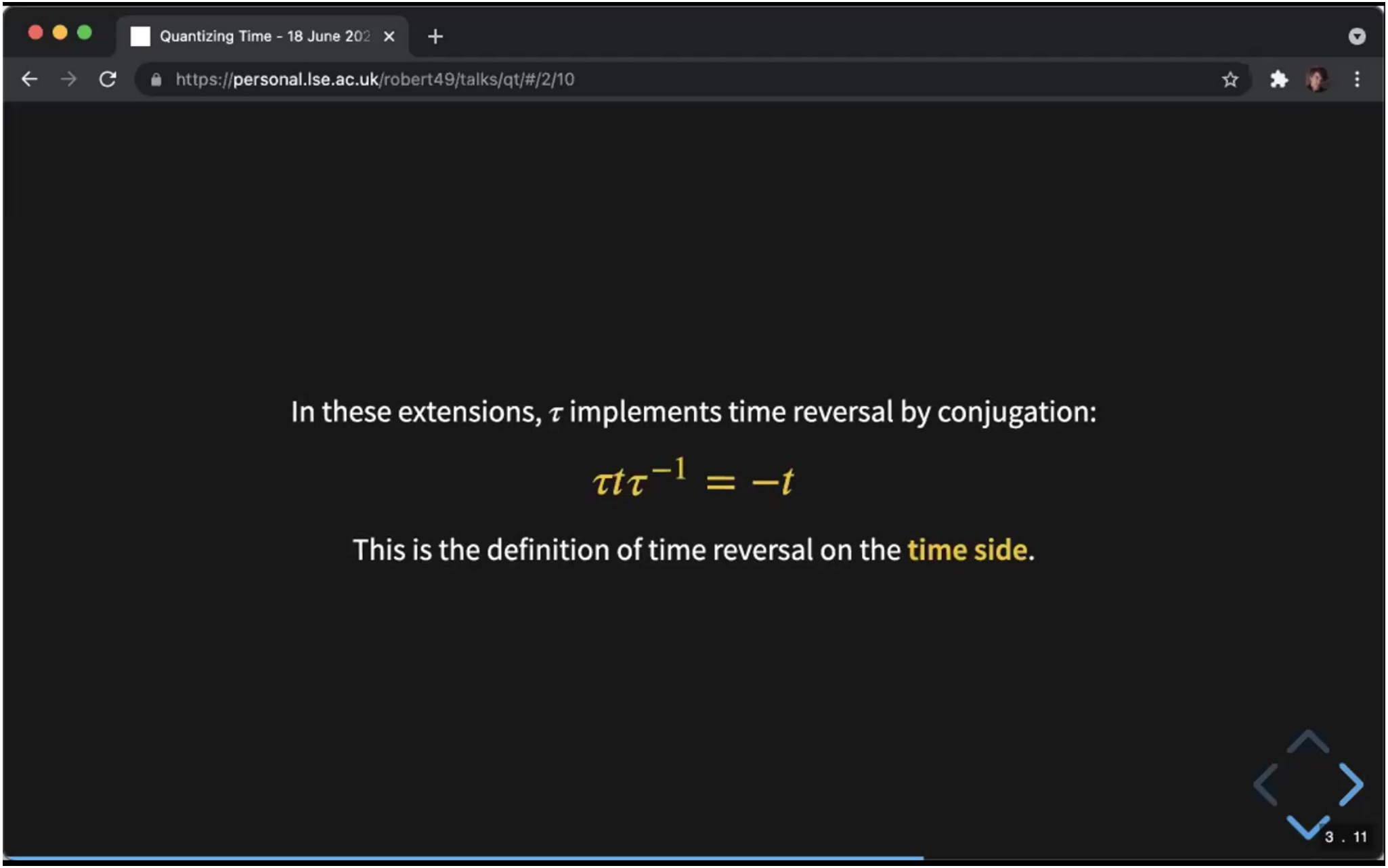
A group S of automorphisms of G defines via the semidirect product an extension of the group to $G \ltimes S$.
• $(\mathbb{R}, +)$ extends to time translations w/time reversal $\tilde{G} = (\mathbb{R}, +) \ltimes \{I, \tau\}$
• $P_+^\uparrow$ extends to the `full' Poincaré group $P = P_+^\uparrow \ltimes \{I, \tau, \pi, \pi\tau\}$
Many references, e.g. Varadarajan (2007)
3 . 10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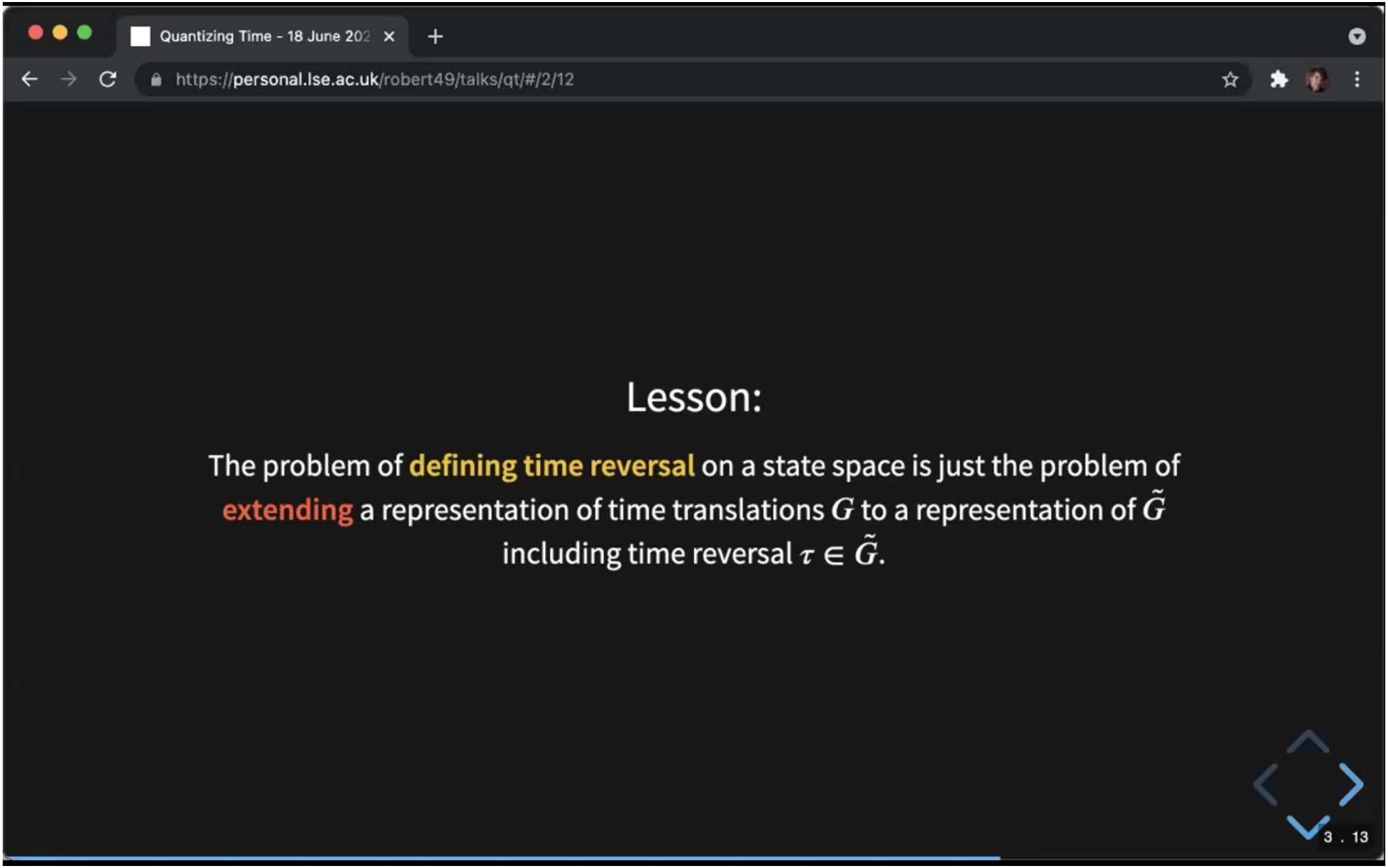
In these extensions, τ implements time reversal by conjugation:
$\tau t \tau^{-1} = -t$
This is the definition of time reversal on the time side.
3 . 11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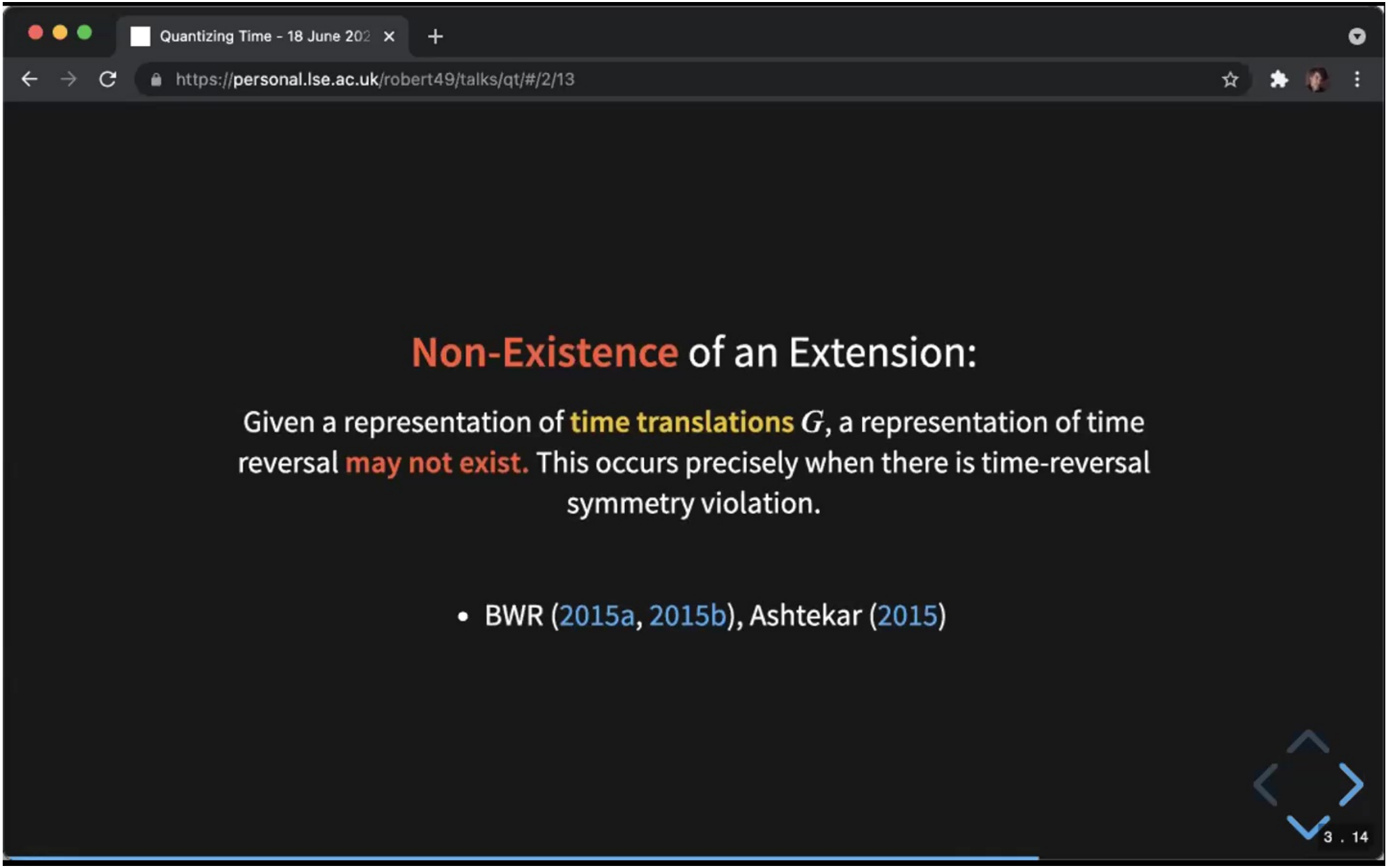
Lesson:
The problem of defining time reversal on a state space is just the problem of extending a representation of time translations G to a representation of $\tilde{G}$ including time reversal $\tau \in \tilde{G}$.
3 . 13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Non-Existence of an Extension:
Given a representation of time translations G, a representation of time reversal may not exist. This occurs precisely when there is time-reversal symmetry violation.
• BWR (2015a, 2015b), Ashtekar (2015)
3 . 14

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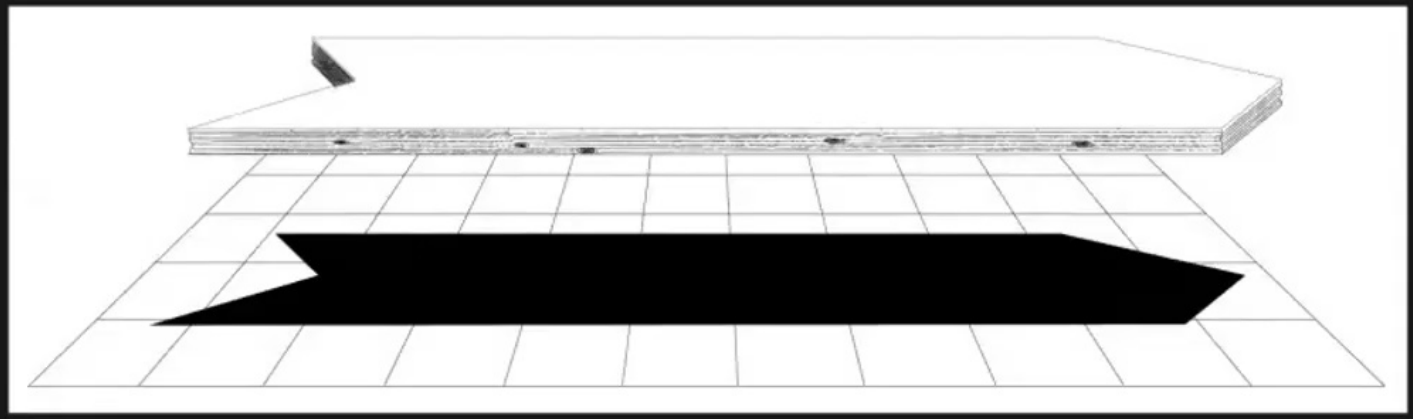
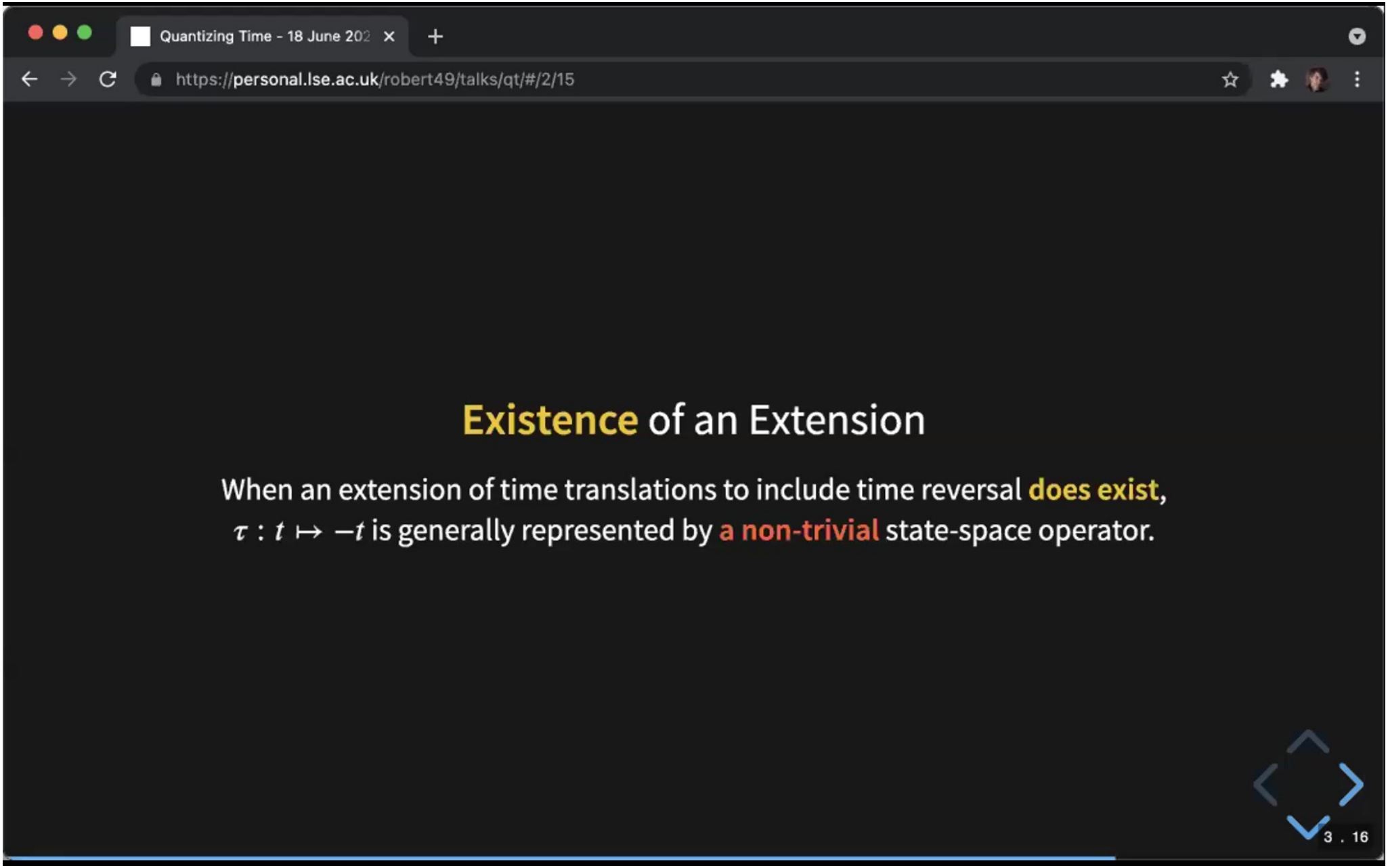
T-violation on state space holds information about the asymmetries of time



...just as a shadow holds information about the asymmetries of the object.

3 . 15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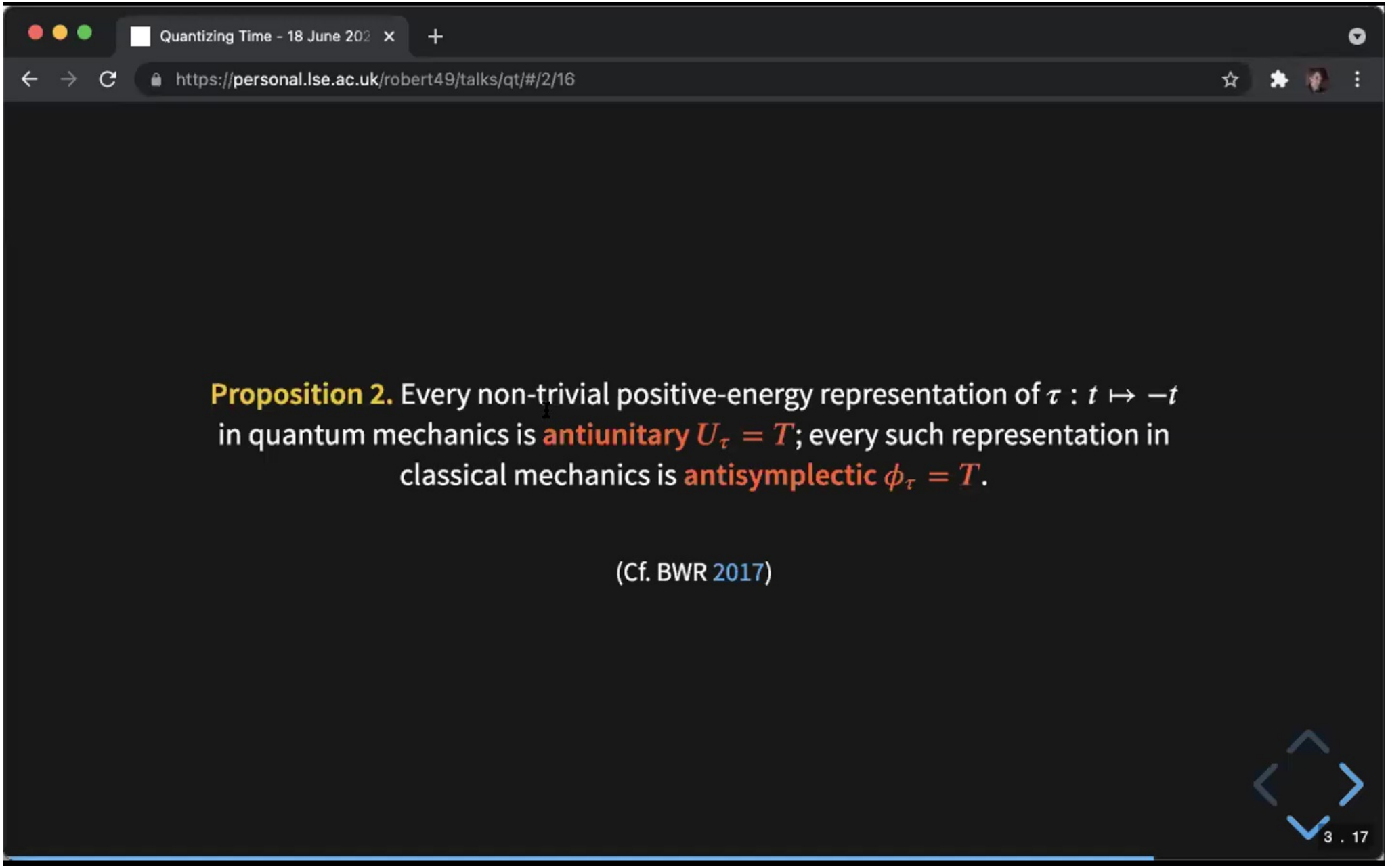
Existence of an Extension
When an extension of time translations to include time reversal does exist,
$\tau : t \mapsto -t$ is generally represented by a non-trivial state-space operator.
3 . 16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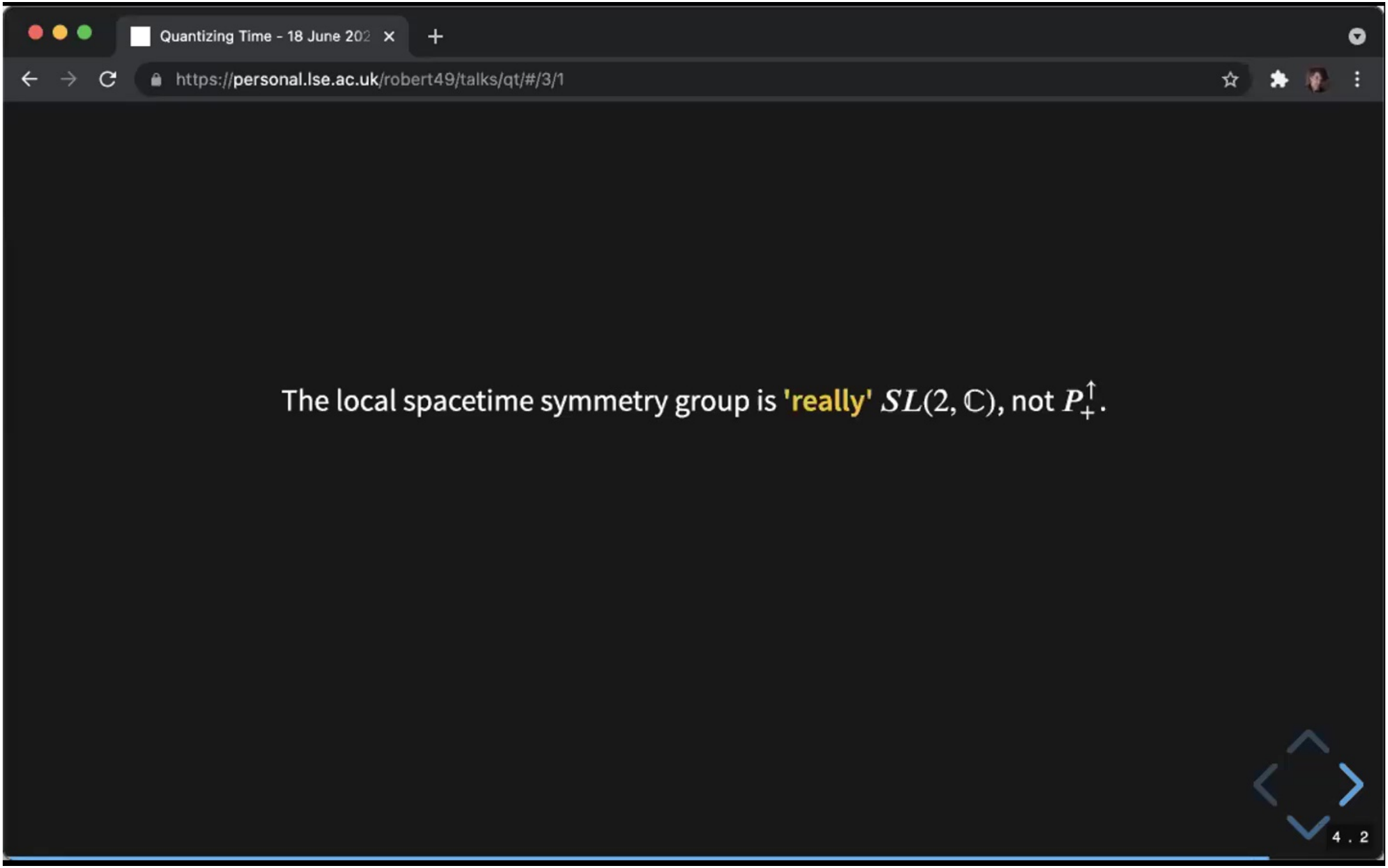
Proposition 2. Every non-trivial positive-energy representation of $\tau : t \mapsto -t$ in quantum mechanics is antiunitary $U_\tau = T$; every such representation in classical mechanics is antisymplectic $\phi_\tau = T$.
(Cf. BWR 2017)
3 . 17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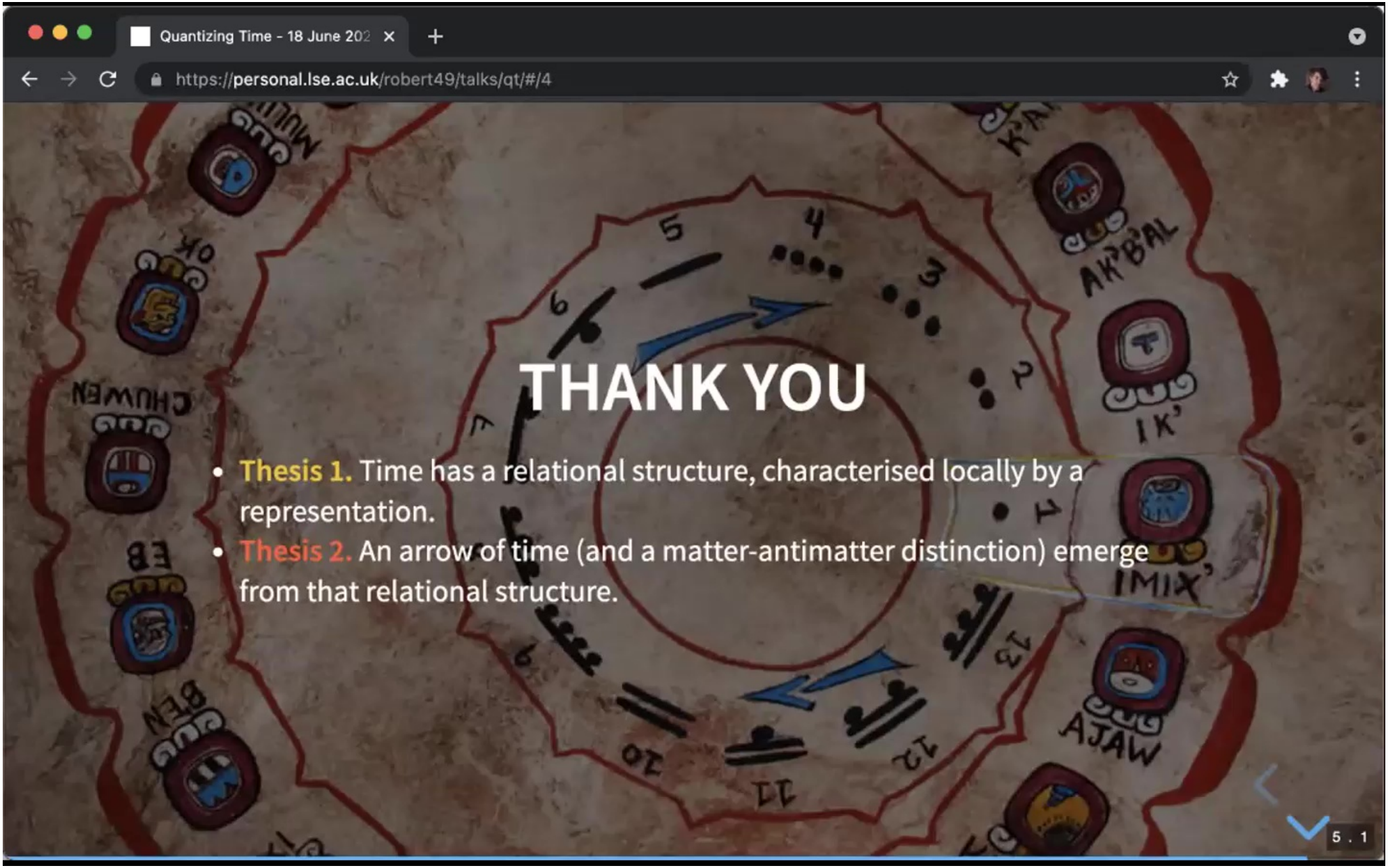
The local spacetime symmetry group is 'really' $SL(2,\mathbb{C})$, not $P_+^\uparrow$.
4 . 2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THANK YOU
Thesis 1. Time has a relational structure, characterised locally by a representation.
Thesis 2. An arrow of time (and a matter-antimatter distinction) emerge from that relational structure.
AK'BAL
IK'
IMIX'
AJAW
5 . 1