Title: Relativistic Quantum State Evolution: Narratability and Relativity

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Abstract: In this talk I will discuss a feature of quantum state evolution in a relativistic spacetime, the feature that David Albert has recently dubbed \'non-narratability.\' This is: a complete state history given along one foliation does not always, by itself (that is, without specification of the dynamics of the system), determine the history along another foliation. The question arises: is this a deep distinction between quantum and classical state evolution, that deserves our fuller attention? I will discuss some results relevant to this question.

Consequences of Entanglement for Quantum State Evolution

Relativity and Narratability

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The Clock and the Quantum Conference
September 30, 2008

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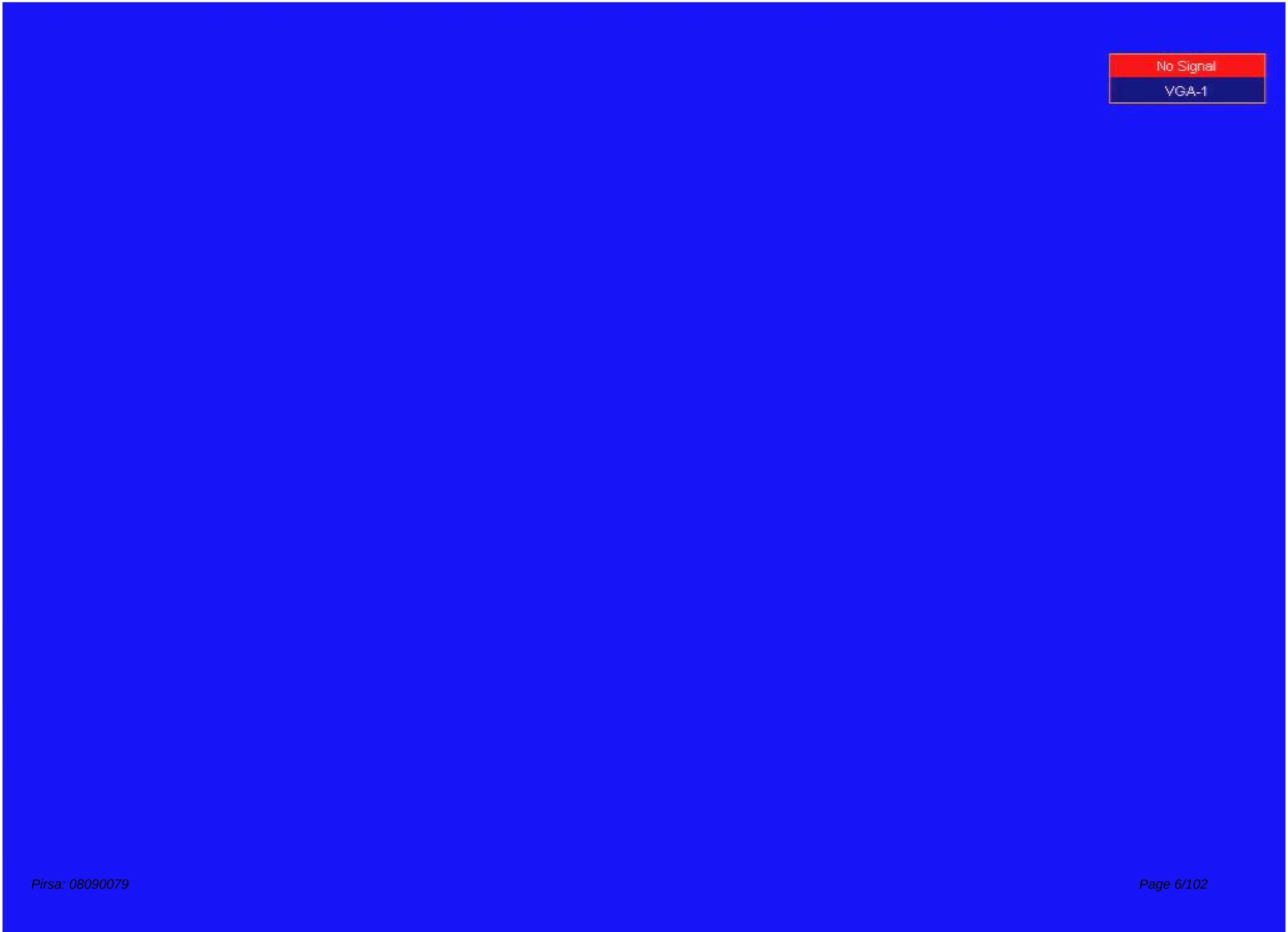
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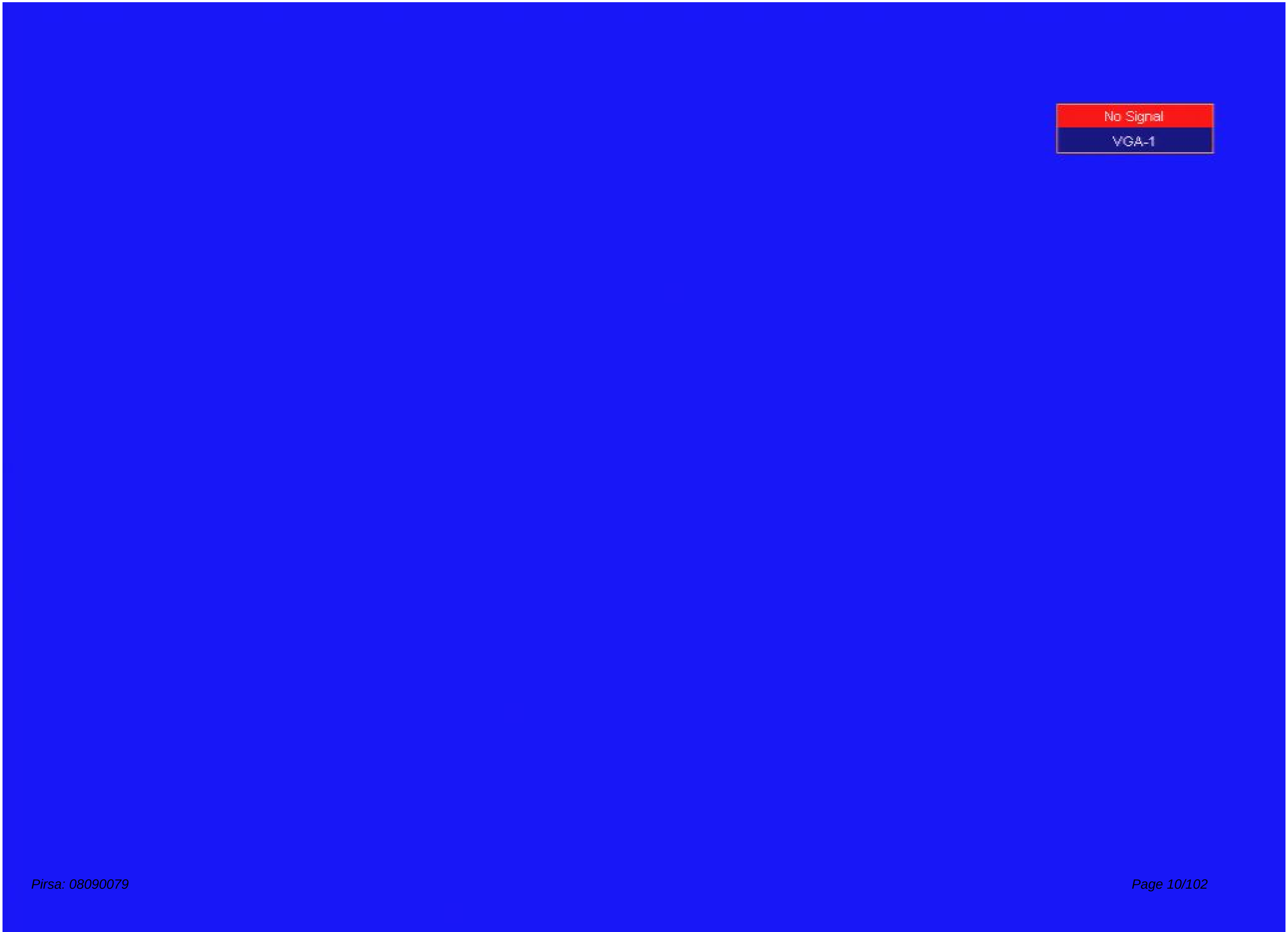
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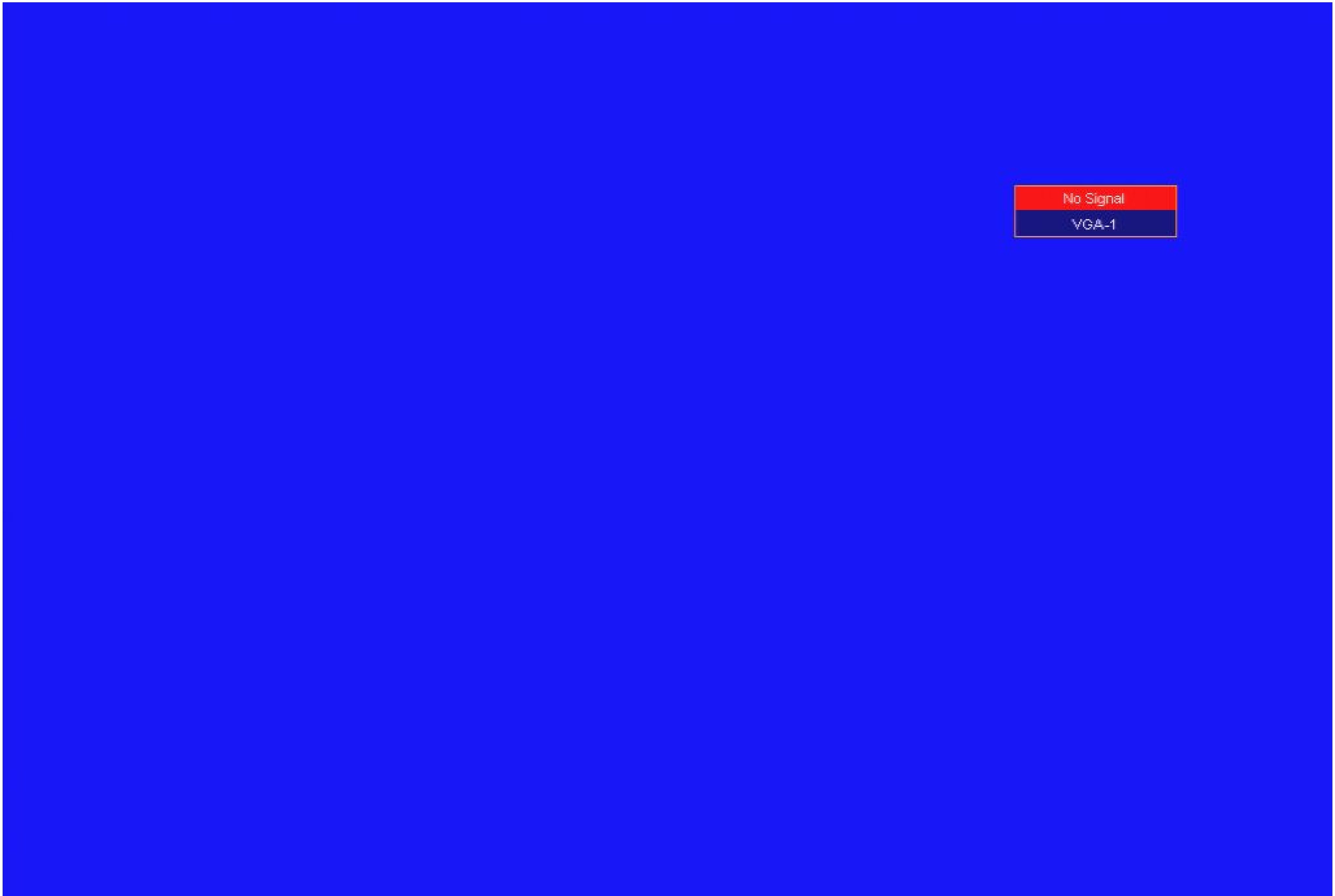
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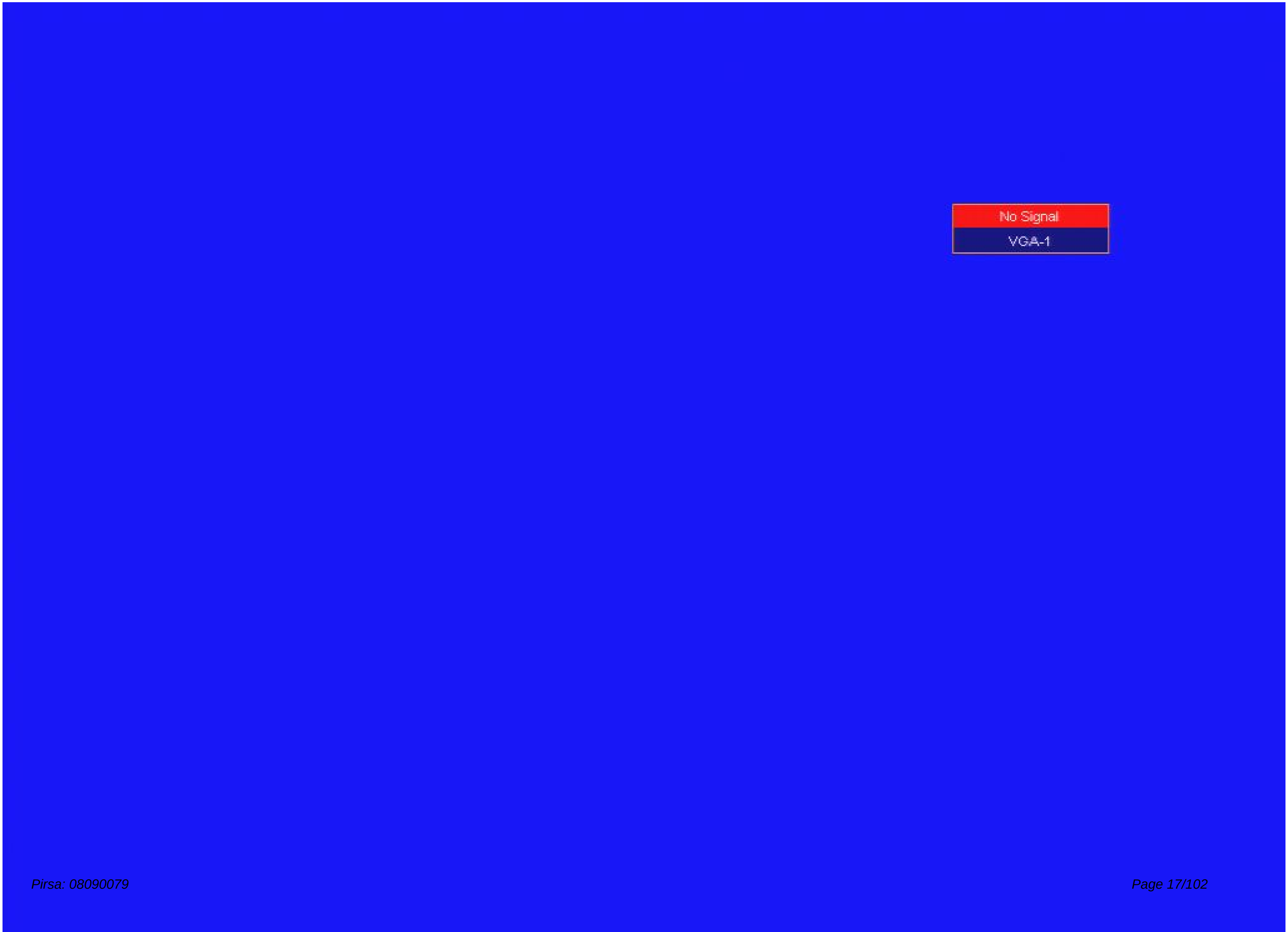
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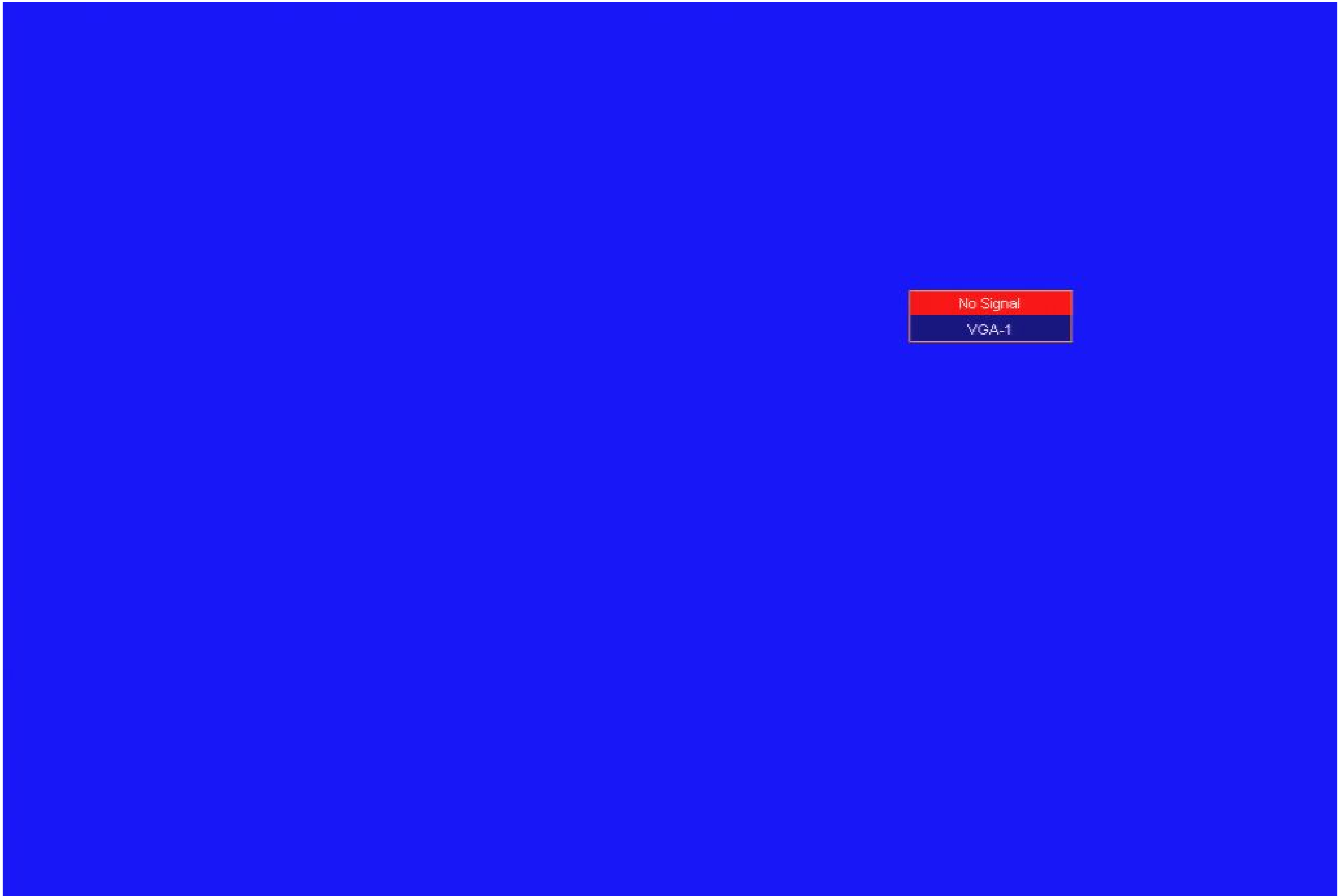
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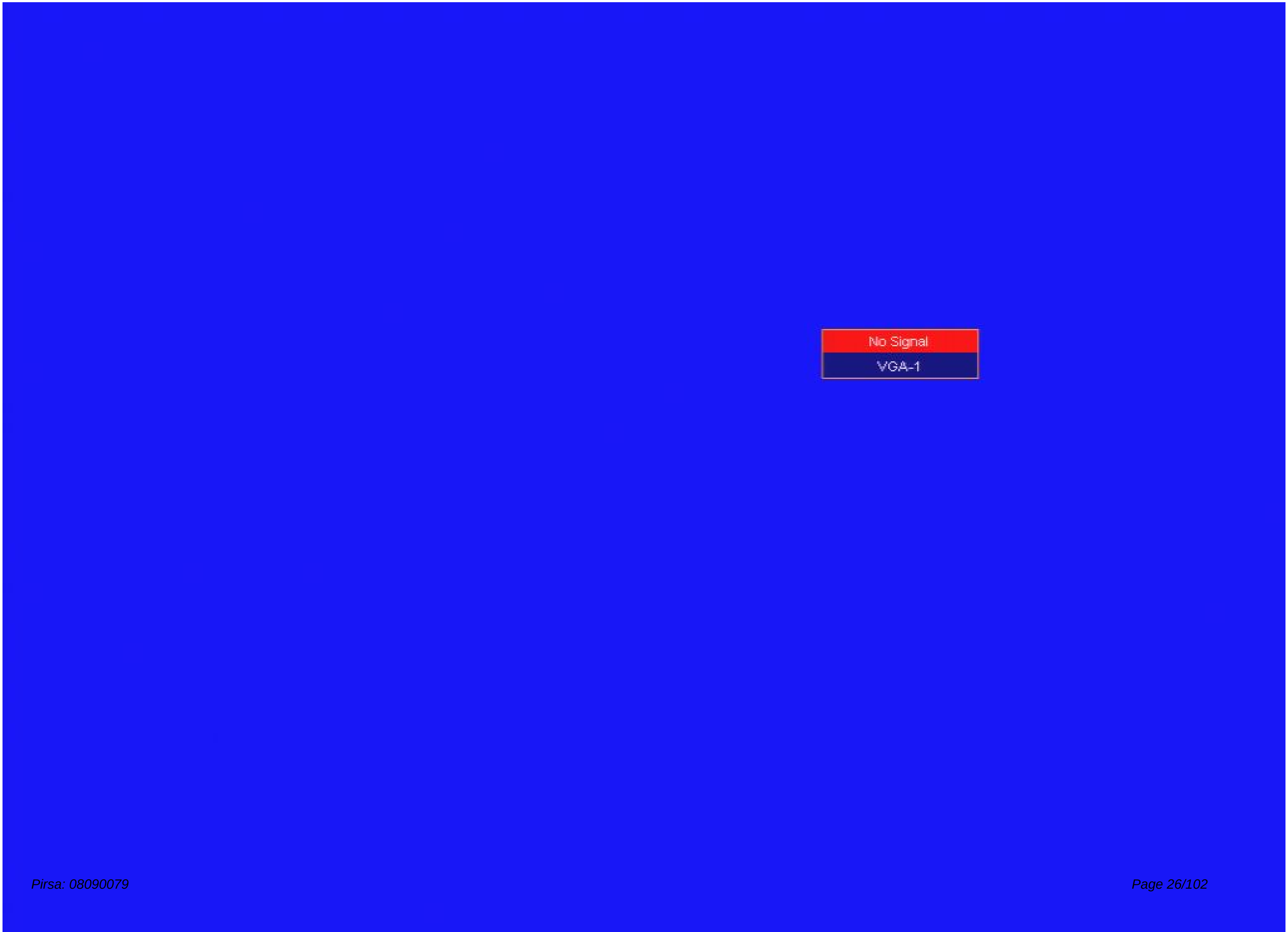
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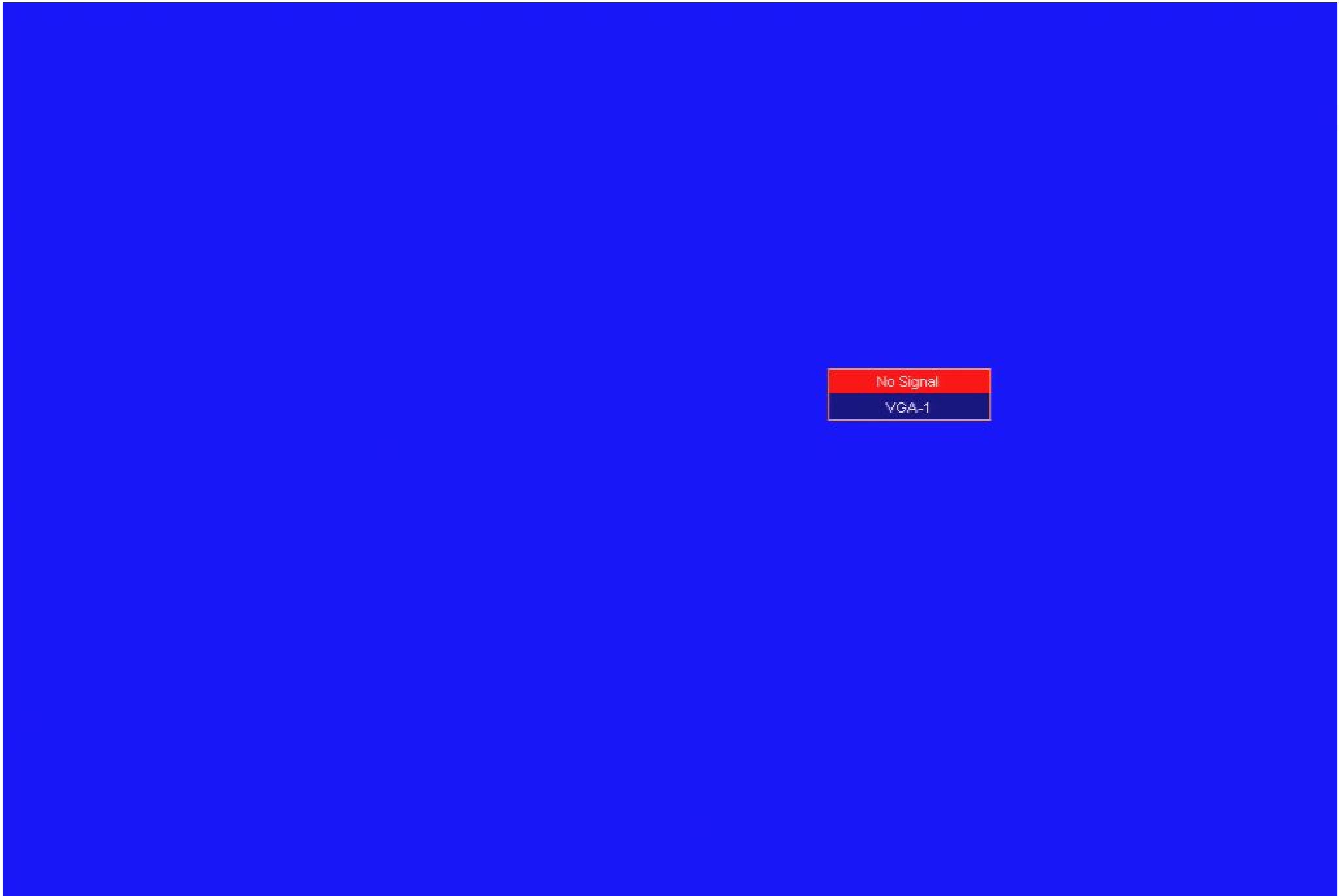
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Schrödinger's dictum

When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz, by endowing each of them with a representative of its own. I would call not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or ψ -functions) have become entangled. (Schrödinger 1935)

Relativistic quantum state evolution

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- "Relativistic Schrödinger picture" or: "Tomonaga-Schwinger picture"?
- To look at: relations between state histories given along different foliations.

Separability and Locality

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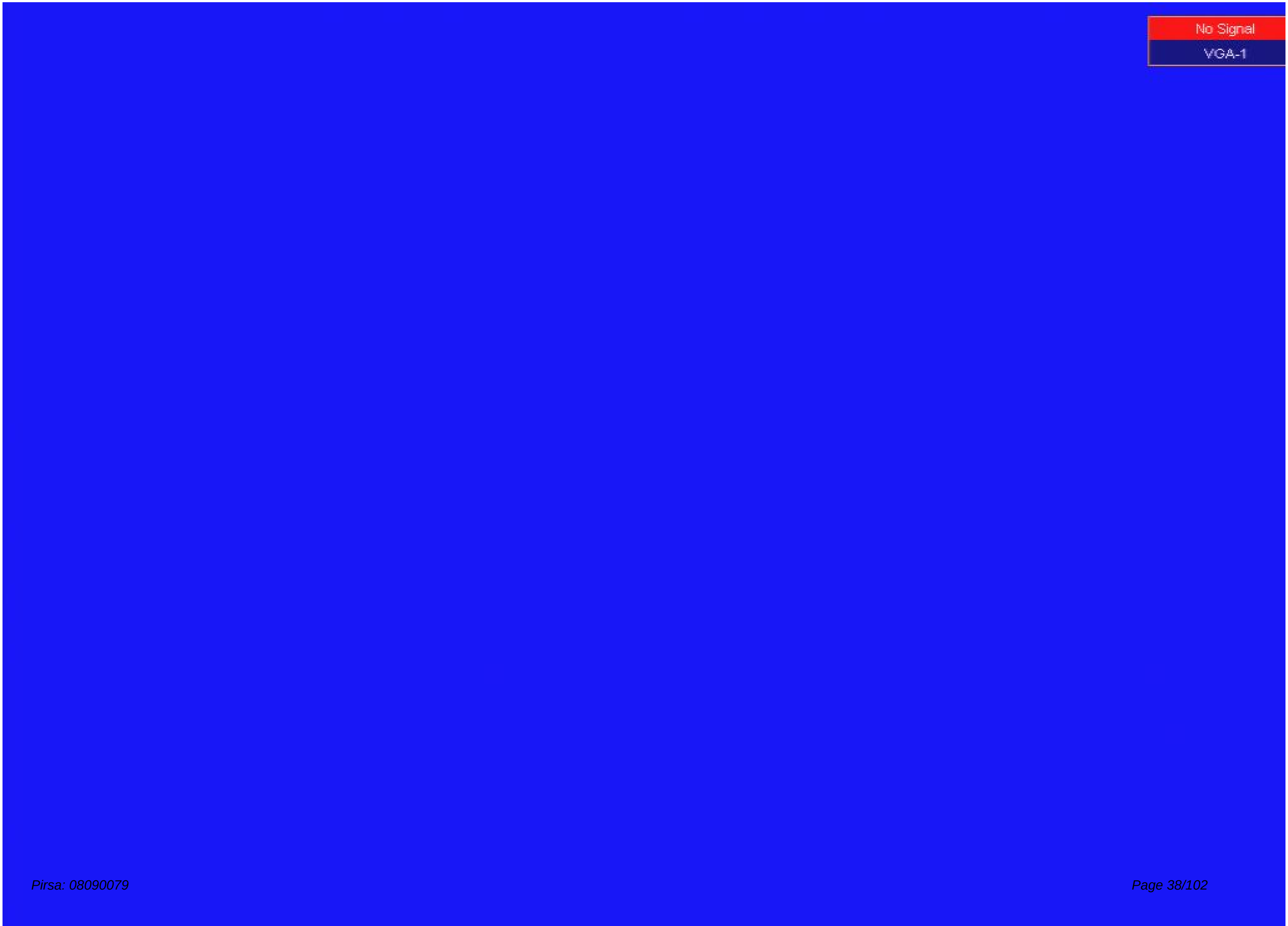
- **Locality**: Interactions are local.
- QM as standardly conceived satisfies *locality*, but quantum state description is non-separable.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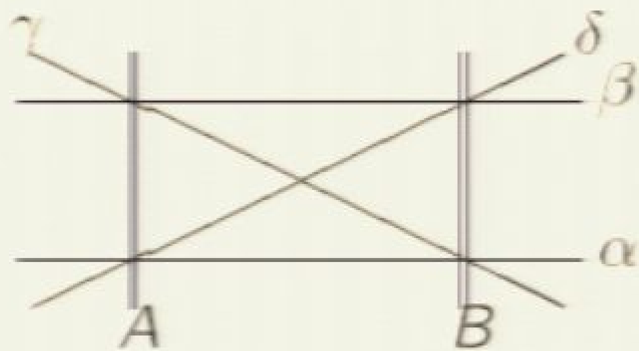
QM in a Relativistic Spacetime



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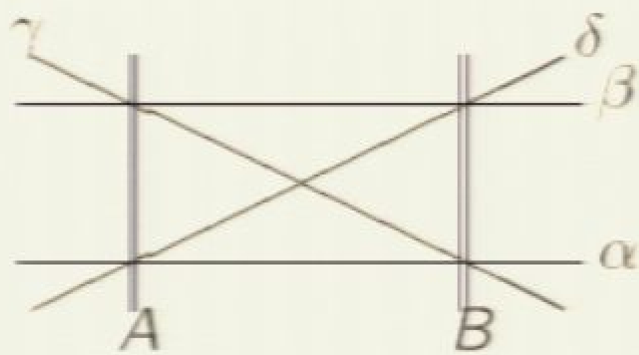

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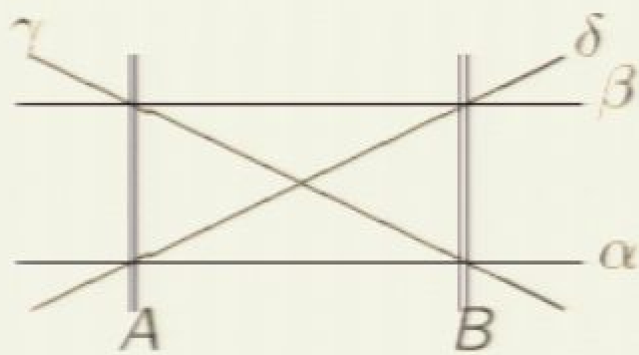

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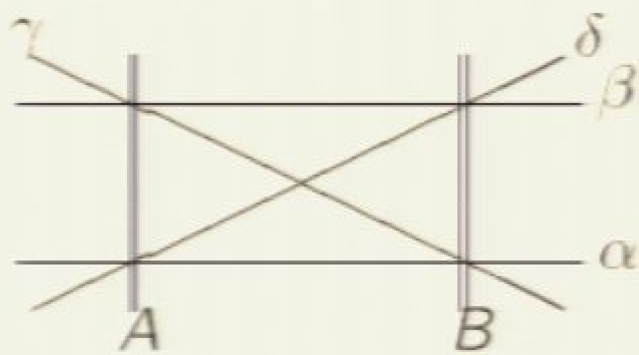
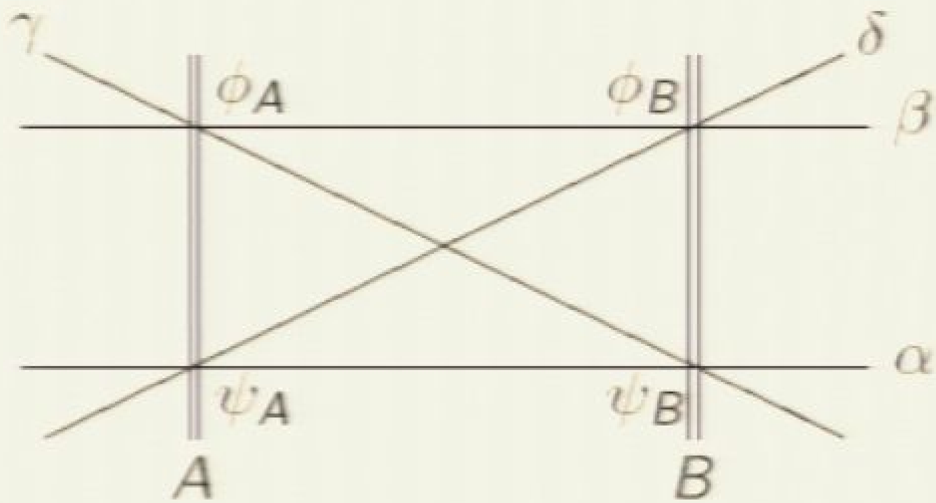


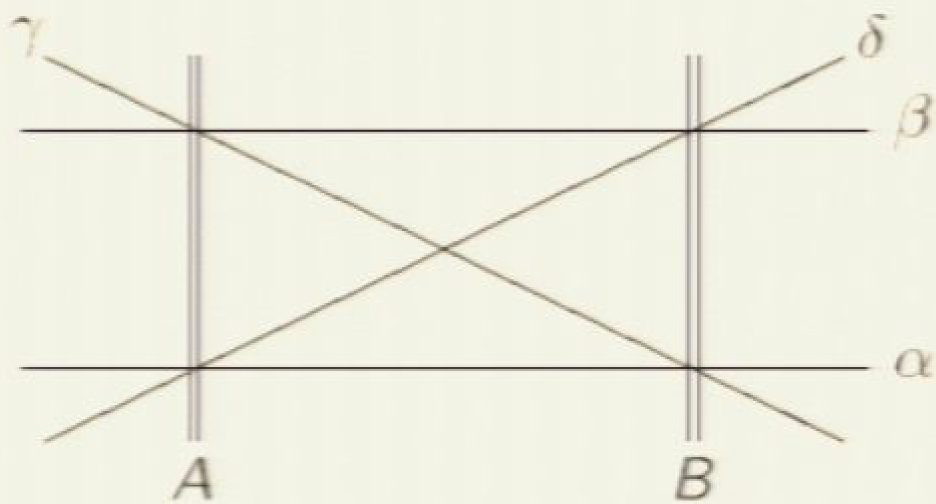
- Consider a finite number of quantum systems, localized in disjoint (and distant) regions of space.
- For each spacelike hypersurface intersecting their world-tubes, there is a state of the combined system.
- Evolution of the combined state is via local evolutions of the component parts:
  - Unitary, if the systems are isolated.

The case of pure product states



- Suppose the states on α and β are pure product states,
  - $\rho(\alpha) = \psi_A \otimes \psi_B$
  - $\rho(\beta) = \phi_A \otimes \phi_B$
- Then these determine $\rho(\gamma)$ and $\rho(\delta)$:
  - $\rho(\gamma) = \phi_A \otimes \psi_B$
  - $\rho(\beta) = \psi_A \otimes \phi_B$

The case of pure entangled states



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- These do not uniquely determine $|\psi(\gamma)\rangle$, $|\psi(\delta)\rangle$.

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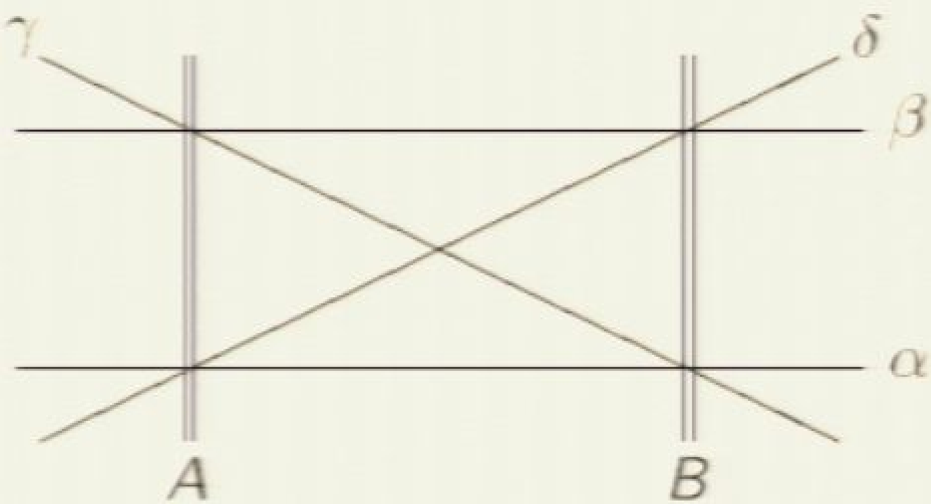

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$$|\psi(\alpha)\rangle = |0\rangle|0\rangle + |1\rangle|1\rangle$$
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- David Albert calls this "non-narratability."
- A complete moment-by-moment history of instantaneous states (without mention of the dynamics that leads from one state to another) is not a complete account of what's going on.

Background to non-narratability

- Aharonov and Albert (1984) consider a system-apparatus interaction that, with respect to some reference frame K (but not others), leaves the system's state unchanged.

  > *The measuring process, so far as K is concerned, disrupts (as it were) the transformation properties of the state and disrupts its covariance, without in any way disrupting the history of the state itself.*

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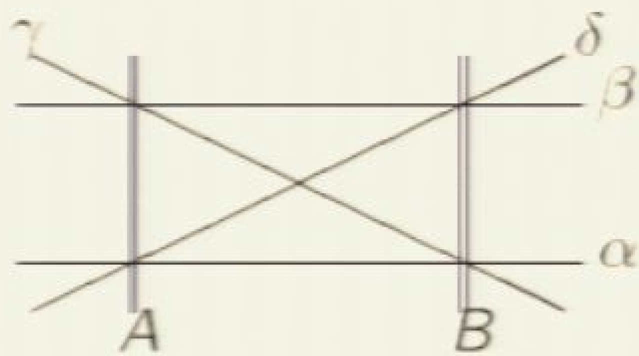
- Myrvold (*SHPMP* 2002) points out that this isn't confined to measurement interactions; simple example involving spin precession.
- Albert (2005) coins term "non-narratability."

How widespread is this?



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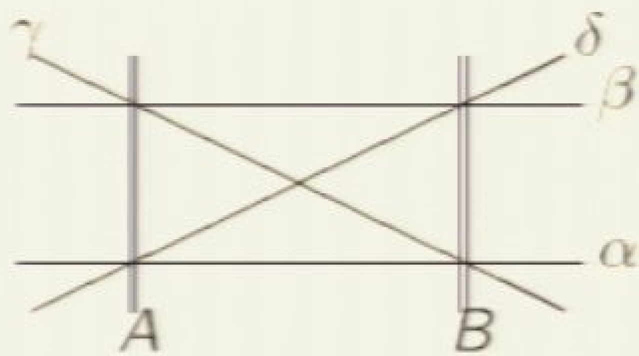

- Suppose I know: $|\psi(\alpha)\rangle$, $|\psi(\beta)\rangle$, and that there is *some* factorizable unitary evolution that relates them.
- Are there unitaries U_A, U_B, U'_A, U'_B, such that

$$|\psi(\beta)\rangle = U_A \otimes U_B\, |\psi(\alpha)\rangle = U'_A \otimes U'_B\, |\psi(\alpha)\rangle$$

but $U_A \otimes I\, |\psi(\alpha)\rangle \neq U'_A \otimes I\, |\psi(\alpha)\rangle$?

Envariance

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then there are unitaries V_A, V_B such that

$$V_A \otimes V_B \, |\psi(\alpha)\rangle = |\psi(\alpha)\rangle$$

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$$V_A \otimes I\,|\psi(\alpha)\rangle \neq |\psi(\alpha)\rangle.$$
- Zurek: If this happens, the state is *envariant* under the transformation V_A.
"Envariance" = "Environmentally assisted invariance."
(quant-ph/0405161)

Extent of the underdetermination

- Write down Schmidt representations

$$|\psi(\alpha)\rangle = \sum_k c_k |a_k\rangle \otimes |b_k\rangle$$

$$|\psi(\beta)\rangle = \sum_k c_k |a'_k\rangle \otimes |b'_k\rangle.$$

Then possible candidates for states on intermediate hypersurfaces are

$$|\psi(\gamma)\rangle = \sum_k c_k |a'_k\rangle \otimes |b_k\rangle$$
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- *All* candidates for the states on γ, δ are obtainable in this way from some Schmidt reps of $|\psi(\alpha)\rangle$, $|\psi(\beta)\rangle$.

Extent of the underdetermination: non-degenerate case

- In the non-degenerate case ($|c_i| \neq |c_j|$ for distinct i, j), undetermination amounts to phase differences: if

$$|\psi(\alpha)\rangle = \sum_k c_k |a_k\rangle \otimes |b_k\rangle$$

$$|\psi(\beta)\rangle = \sum_k c_k |a'_k\rangle \otimes |b'_k\rangle.$$

then, for some $\{\theta_k\}$,

$$|\psi(\gamma)\rangle = \sum_k c_k e^{i\theta_k} |a'_k\rangle \otimes |b_k\rangle. \qquad |\psi(\delta)\rangle = \sum_k c_k e^{-i\theta_k} |a_k\rangle \otimes |b'_k\rangle$$

Bipartite systems in pure initial state: Non-narratability is generic

- For any unitary evolution $U_A(t) \otimes U_B(t)$, along a foliation F, and any pure entangled initial state, there are alternate evolutions $U'_A(t) \otimes U'_B(t)$ that produce the same state history along F, but different state histories along other foliations.

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- The set of pure entangled states of a bipartitie system is an open, norm-dense set in the set of pure states; in this sense entanglement is *generic*.
- If the systems are not isolated, evolution will be given by completely positive maps $\varphi_A(t) \otimes \varphi_B(t)$.
- As long as these don't destroy phase information in the Schmidt basis (thereby disentangling A and B), we will be able to find alternate maps $\varphi'_A(t)$, $\varphi'_B(t)$ that yield same state history along F, but differ along other foliations.

Bipartite systems in mixed state; tripartite systems

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- Consider a system consisting of three spacelike separated parts, A, B, C, and suppose

$$|\psi(\alpha)\rangle = |\psi(\beta)\rangle = \sum_k c_k |a_k\rangle_A |\Phi_k\rangle_{BC}$$

- Apply previous theorem:

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- If $\theta_i \neq \theta_j$, this will be achievable by *local* evolutions only if $|\Phi_i\rangle_{BC}$ and $|\Phi_j\rangle_{BC}$ are *locally* distinguishable.
- This fails for an open, norm-dense set of pure states of ABC.

Same result, another way

- Suppose bipartite system AB, factorizable unitary evolution,
- Orthogonal decomposition of initial state:

$$\rho(\alpha) = \sum_k w_k \, \delta_k .$$

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- Unitary evolution leaves each of these states pure, and orthogonal.

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  - **Weak Narratability**: A state history along with foliation, together with the constraint that evolution is *some* local evolution permitted by the theory, uniquely determines a state history along any other foiiation.
- Only state histories consisting of pure product states satisfy strong narratability.

Nonseparability in non-quantum theories

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- It can be useful to compare QM to other theories, including theories that result from classical set-up by imposing restrictions on state preparation and measurements. (*e.g* Spekkens).
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- Entangled states: pure states with mixed marginals.

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- Pure states of the theory: states that are not mixtures of permitted states.
- Entangled states: pure states with mixed marginals.
- Will **every** theory that contains entangled states exhibit non-narratability?

Non-narrativity in any theory with entangled states.

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Non-narrativity in any theory with entangled states.

- A has two isomorphic subsystems, A_1 and A_2
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- Suppose that any local automorphism is a physically possible transformation.

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- A necessary condition: there are local transformations that change the state, but leave the marginals invariant.

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- Superiority of the Heisenberg picture? (Deutsch's remark.)