Rapid Bombardment is not Thermal Contact

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We show it fundamentally can not. We argue:

1) Thermal contact can be used to measure temperatures.

2) Any temperature measurement procedure (e.g. thermal contact) must involve the system's free energy scale.

3) Learning the energy scale of a thermal state takes time.

Conclusion: Rapid bombardment is not thermal contact.

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Defining thermal states as $\rho = \exp(-\beta \hat{H})/Z$ for some inverse temperature, β, and Hamiltonian, $\hat{H}$, and partition function, $Z = \mathrm{Tr}(\exp(-\beta \hat{H}))$, we can view the zeroth law as a defining property of thermal contact.

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You can determine whether or not two systems are at the same temperature by placing them in thermal contact.

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$$\Lambda : \beta \to \lambda\, \beta, \quad \hat{H} \to \hat{H}/\lambda \tag{1}$$

such that $\beta_A \neq \beta_C$ but $\rho_{\text{A}} = \rho_{\text{C}}$. As a concrete example, imagine a spin qubit with a higher temperature in a stronger magnetic field.

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What gives? What information is state tomography missing?

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Recall that we can us thermal contact to measure temperatures.
The dynamics underlying thermal contact must sense this energy scale.

A Concrete (Mischievous) Scenario

What if the dynamics underlying thermal contact does not depend on this energy scale? Consider the following scenario:

1) You place A and B in (alleged) thermal contact and confirm that they are at the same temperature, that is $\beta_{\mathsf{A}} = \beta_{\mathsf{B}}$.

2) The trickster god, Loki, swaps out system A with system $C = \Lambda[A]$ with $\beta_{\mathsf{C}} \neq \beta_{\mathsf{A}}$ but $\rho_{\mathsf{C}} = \rho_{\mathsf{A}}$.

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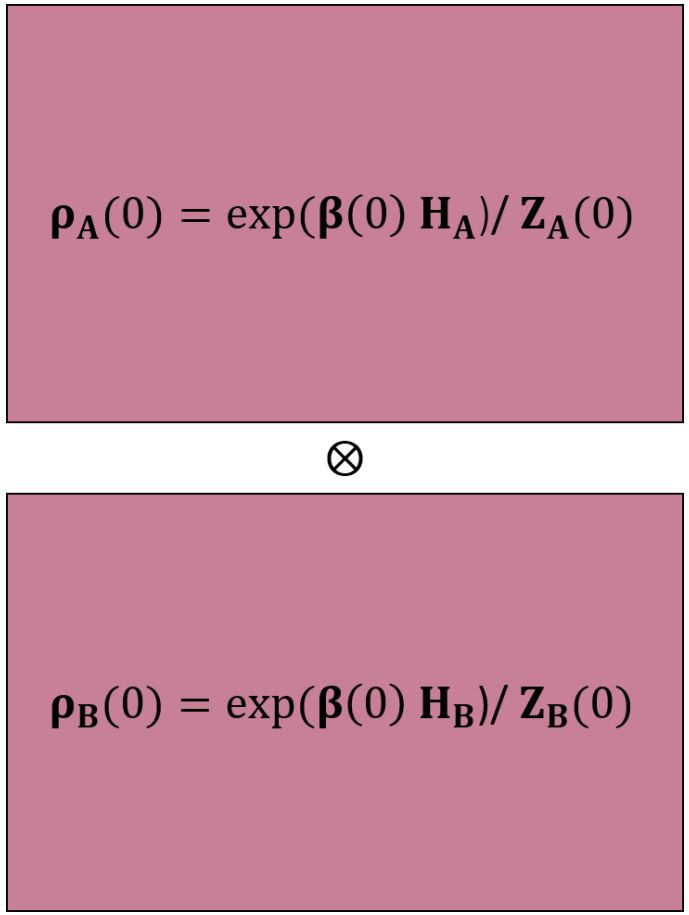
What should happen?



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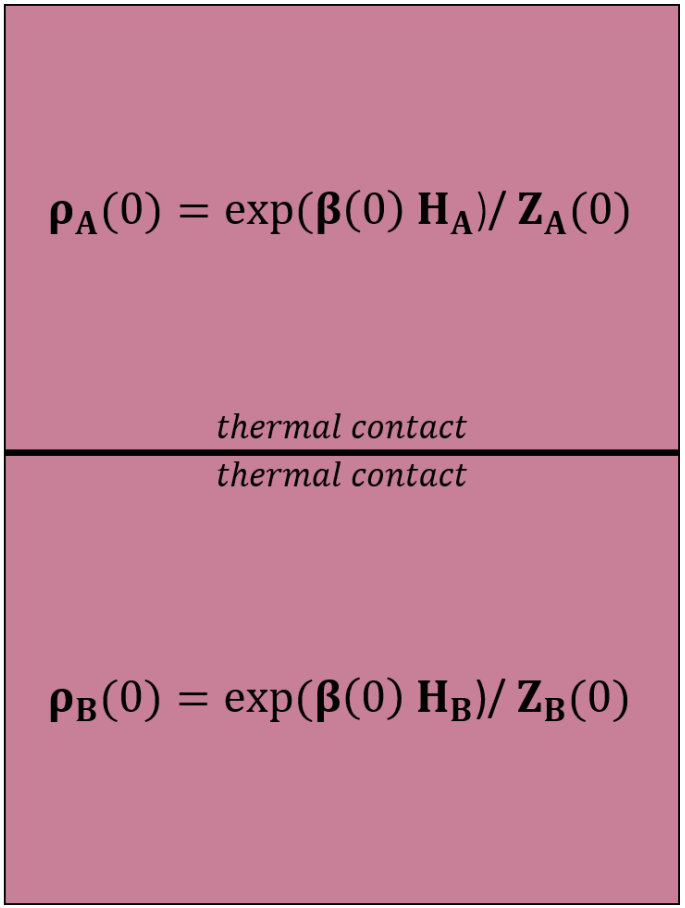

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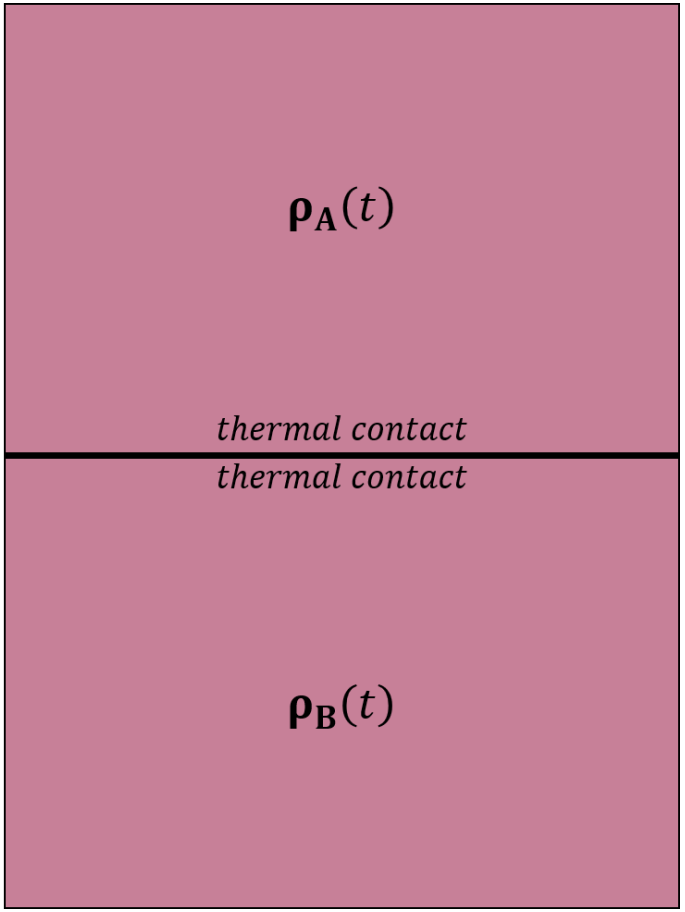

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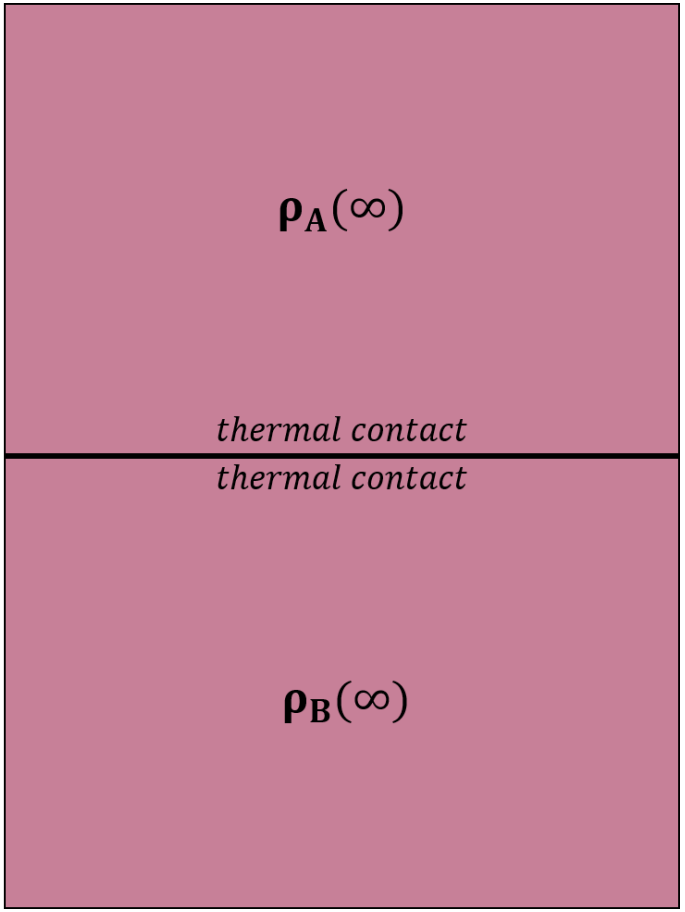

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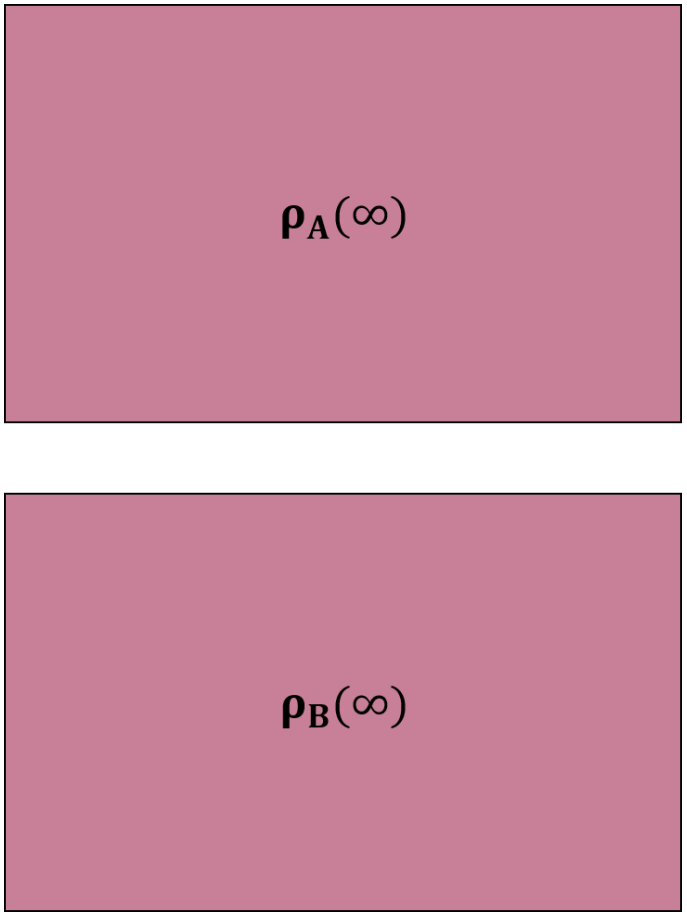

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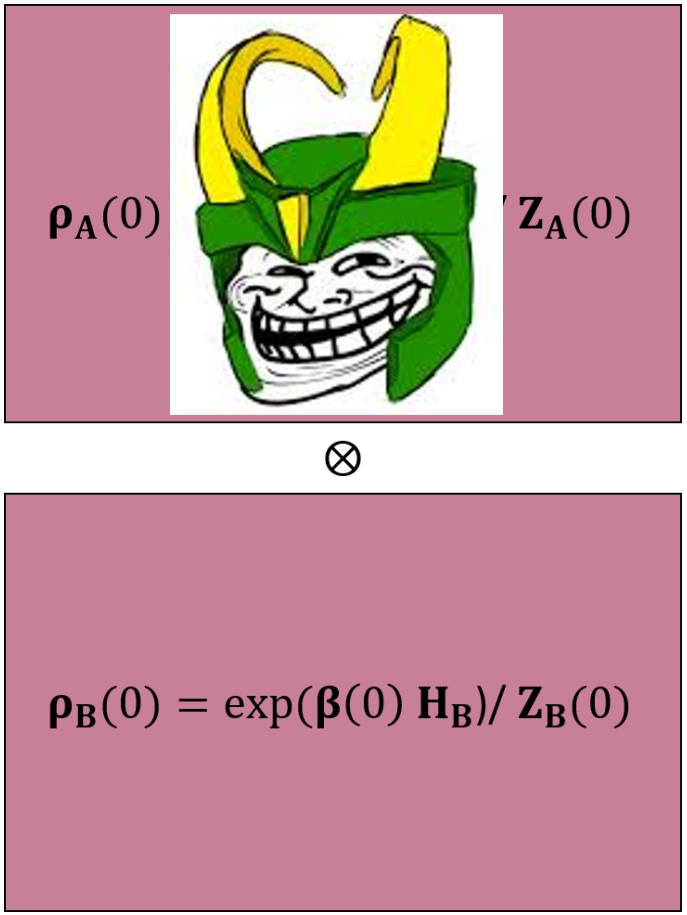

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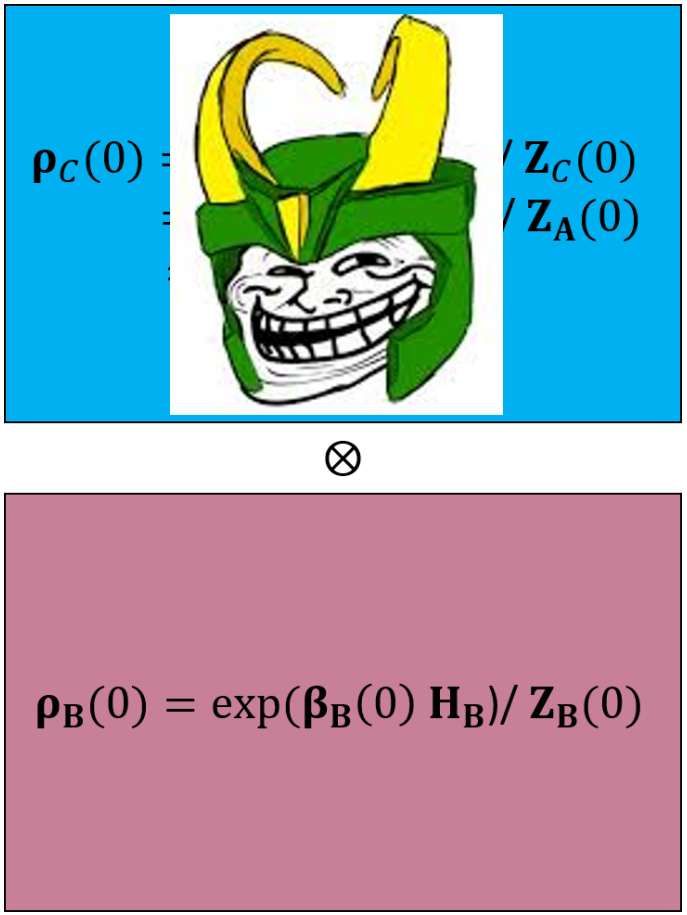

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$$\begin{aligned}\boldsymbol{\rho}_C(0) &= \exp(\boldsymbol{\beta}_C(0)\,\mathbf{H}_C)/\,\mathbf{Z}_C(0)\\ &= \exp(\boldsymbol{\beta}_{\mathbf{A}}(0)\,\mathbf{H}_{\mathbf{A}})/\,\mathbf{Z}_{\mathbf{A}}(0)\\ &= \boldsymbol{\rho}_{\mathbf{A}}(0)\end{aligned}$$

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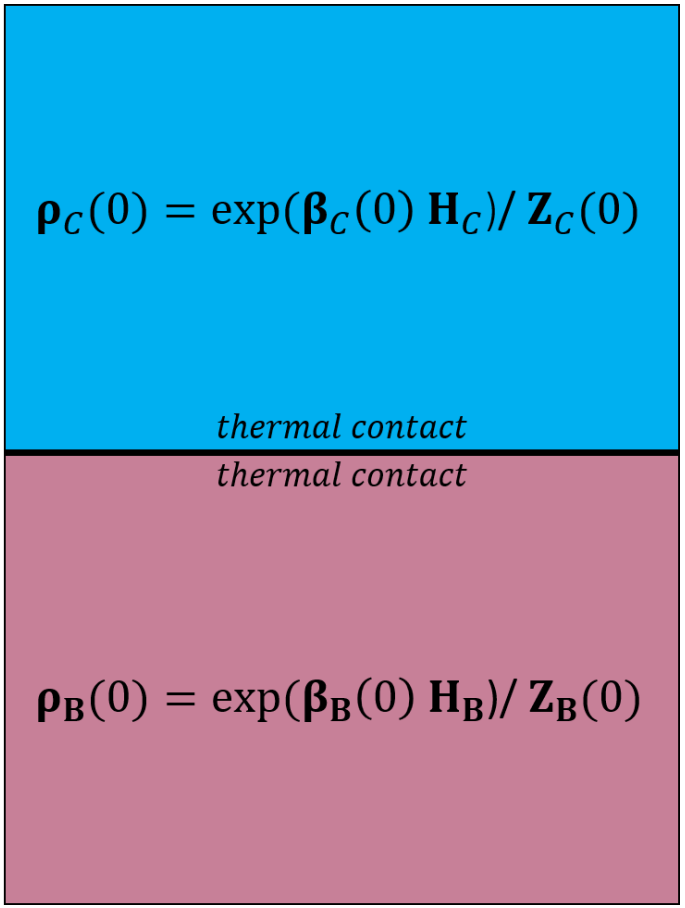

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If the alleged thermal contact is in fact thermal contact, then we should see heat to flow between C and B.

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In order to be resistant to Loki's trickery, the dynamics underlying thermal contact must involve the systems' local Hamiltonians.

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$$\hat{H} = \hat{H}_{\mathsf{A}} \otimes \mathbb{1}_{\mathsf{B}} + \mathbb{1}_{\mathsf{A}} \otimes \hat{H}_{\mathsf{B}} + \hat{H}_{\mathsf{AB}}$$

then it is repeatedly updated, $\rho_{\mathsf{B}}(n\,\delta t) = \phi(\delta t)^n[\rho_{\mathsf{B}}(0)]$, by the CPTP map

$$\phi(\delta t)[\rho_{\mathsf{B}}] = \mathsf{Tr}_{\mathsf{A}}\Big(\exp(-\mathrm{i}\,\delta t\,\hat{H}/\hbar)(\rho_{\mathsf{B}} \otimes \rho_{\mathsf{A}}) \exp(\mathrm{i}\,\delta t\,\hat{H}/\hbar)\Big).$$

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If the bombardment is rapid enough we can truncate this expansion.

How long does it take to sense temperature?

Which ϕ_k in $\phi(\delta t) = \mathbb{1} + \delta t\, \phi_1 + \delta t^2\, \phi_2 + \delta t^3\, \phi_3 + \ldots$ depend on $\hat{H}_{\mathrm{A}}$?

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Viewing $\delta t[\hat{H}_X, \rho]$ as evolution with respects to $\hat{H}_X$, we interpret this as:

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1) Interact with it (so that it isn't thermal anymore)
2) Let it freely evolve (enter dependence on its energy scale)
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If the bombardment is rapid enough this process is highly suppressed.

[2] ArXiv:1805.11118 "Thermal Contact: Mischief and Time Scales" Daniel Grimmer, Robert B. Mann, Eduardo Martín-Martínez

How long does it take to sense temperature?

Which ϕ_k in $\phi(\delta t) = \mathbb{1} + \delta t\, \phi_1 + \delta t^2\, \phi_2 + \delta t^3\, \phi_3 + \ldots$ depend on $\hat{H}_\mathrm{A}$?

Assuming ρ_A is thermal, we find[2] that ϕ_1 and ϕ_2 do not depend on $\hat{H}_A$. We find ϕ_3 can through terms $\sim \delta t^3\, \mathrm{Tr}_\mathrm{A}\big([\hat{H}_\mathrm{AB}, [\hat{H}_\mathrm{A}, [\hat{H}_\mathrm{AB}, \rho_\mathrm{B} \otimes \rho_\mathrm{A}]]]\big)$.

Viewing $\delta t[\hat{H}_X, \rho]$ as evolution with respects to $\hat{H}_X$, we interpret this as: Learning the free energy scale (and therefore the temperature) of a thermal system, ρ_A, takes at least three steps:

1) Interact with it (so that it isn't thermal anymore)
2) Let it freely evolve (enter dependence on its energy scale)
3) Interact with it again (to get the information out)

If the bombardment is rapid enough this process is highly suppressed.
Learning the temperature of a thermal systems takes time.

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Conclusion

What have we learned today?

1) Thermal contact can be used to measure temperatures.

2) Any temperature measurement procedure (e.g. thermal contact) must involve the system's free energy scale.

3) Learning the energy scalee of a thermal systems takes time.

Final Conclusion: Rapid Bombardment is not thermal contact.

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Consider a molecule placed in the air at room temperature ($T = 300$ K) and pressure ($P = 1$ atm) interacting with the nearest Nitrogen molecule ($m_{N_2} = 28$ amu).

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Thus the interactions in the air are (thankfully) long enough to sense the ambient temperature. This bombardment is not rapid.