Title: Physics From Loop Quantum Gravity

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Abstract:

Physics from LQG

Lee Smolin
Perimeter Institute for Theoretical Physics

1 Questions about locality in LQG
2 Options
3 Effects and implications of non-locality in LQG
4 Conclusions

Work with Fotini Markopoulou gr-qc/0311059
hep-th/0411???

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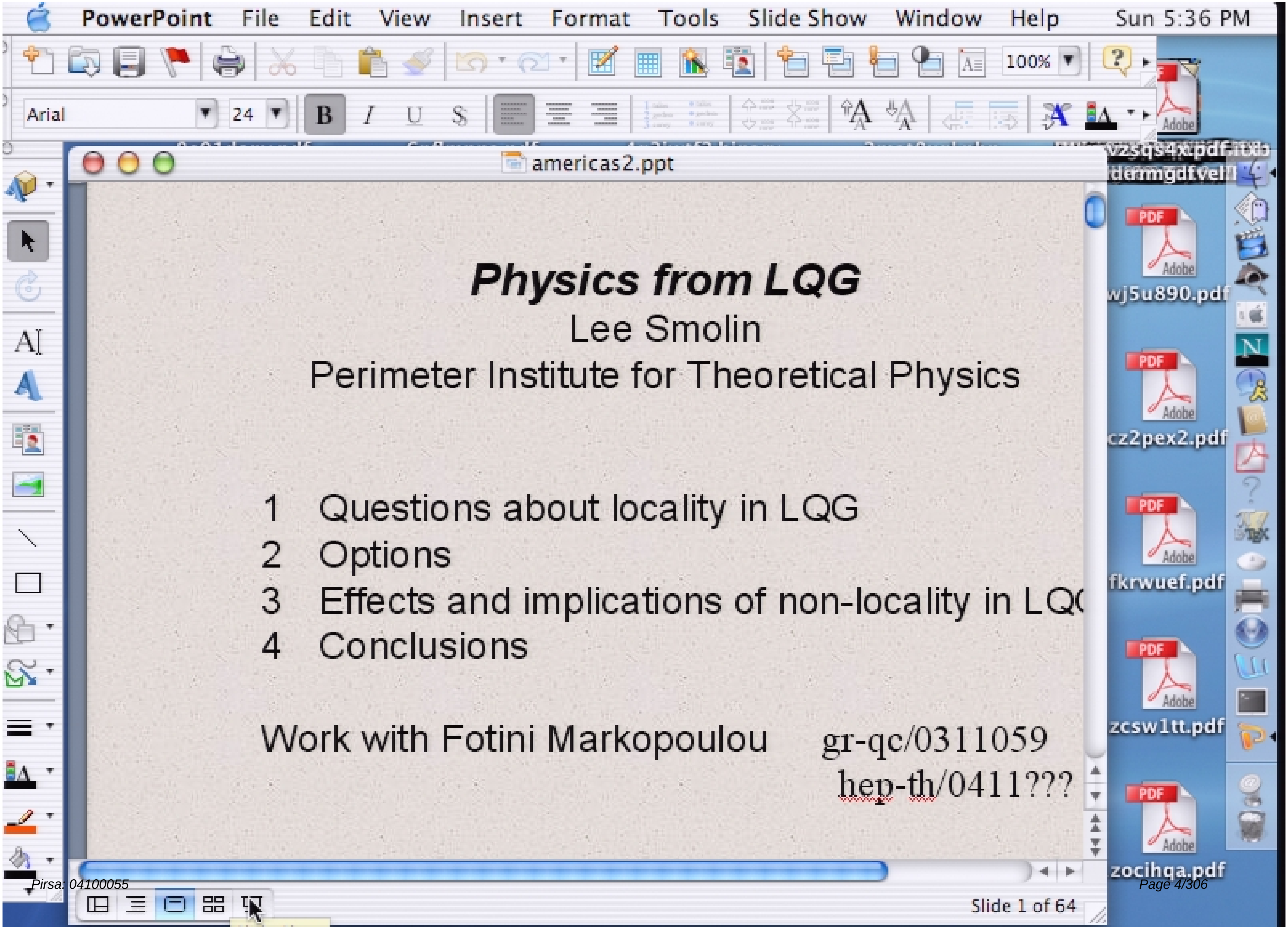
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Slide 1 of 64

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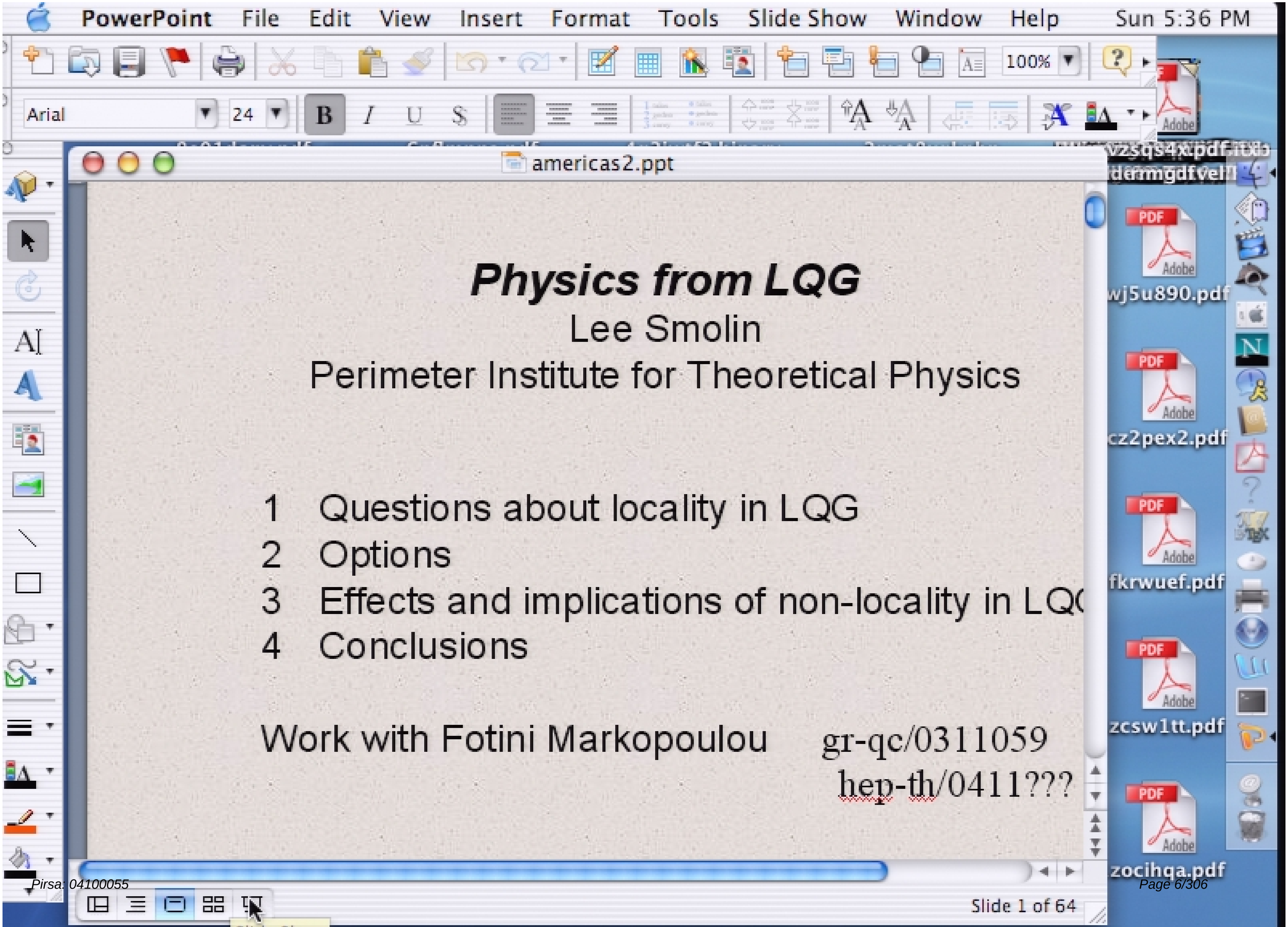
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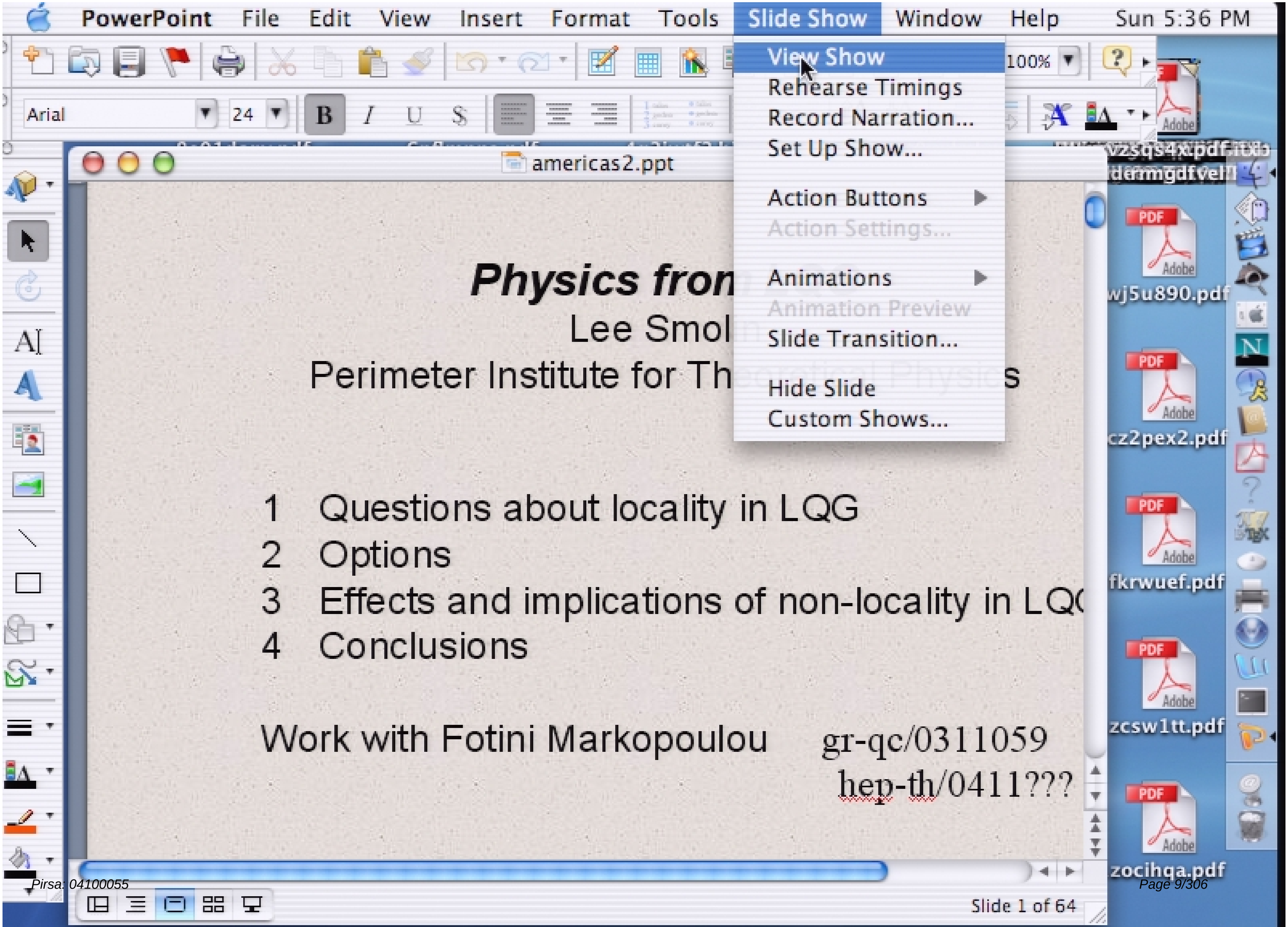
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Slide 1 of 64
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Several speakers have refered to issues with locality in LQG and other approaches such as causal sets.

The basic worry is that when we study spin foams and weaves we impose locality because we believe in it. But this is not forced by the theory. We could make other choices that introduce arbitrary amounts of non-locality.

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Do weaves have to be local?

A state $|\Psi>$ is a weave for a metric q_{ab} if the <>'s of areas and volumes coincide for large regions with the classical values:

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< \Psi|\hat{\mathcal{A}}[\mathcal{F}]|\Psi > &= \left(a[\mathcal{F}] + O(\frac{l_{Pl}^2}{a[\mathcal{F}]} \right) \\
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Regular graph state: Γ be a graph, all edges have spin j all nodes intertwiner I $|\Gamma, j, I>$

Local weave: *all links connect nodes of order* l_P *apart in* q_{ab}

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Superposed weaves:

$$|\Psi >= \sum_{j=\frac{1}{2}}^{\infty} \sum_{I \in \mathcal{V}_{jjjj}} a_{j,I} |\Gamma, j, I>$$

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Regular graph state: Γ be a graph, all edges have spin j all nodes intertwiner I $|\Gamma, j, I >$

Local weave: *all links connect nodes of order l_P apart in q_{ab}*

.

Superposed weaves:

$$|\Psi >= \sum_{j=\frac{1}{2}}^{\infty} \sum_{I \in \mathcal{V}_{jjjj}} a_{j,I}|\Gamma, j, I > \qquad \sum_{j=\frac{1}{2}}^{\infty} \sum_{I \in \mathcal{V}_{jjjj}} |a_{j,I}|^2 = 1$$

Do weaves have to be local?

A state $|\Psi>$ is a weave for a metric q_{ab} if the <>'s of areas and volumes coincide for large regions with the classical values:

$$
\begin{aligned}
< \Psi|\hat{\mathcal{A}}[\mathcal{F}]|\Psi > &= \left(a[\mathcal{F}] + O(\frac{l_{Pl}^2}{a[\mathcal{F}]}\right) \\
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Solutions: Bombelli weaves:

$$\sum_{j=\frac{1}{2}}^{\infty} \sum_{I \in \mathcal{V}_{jjjj}} |a_{j,I}|^2 = 1$$

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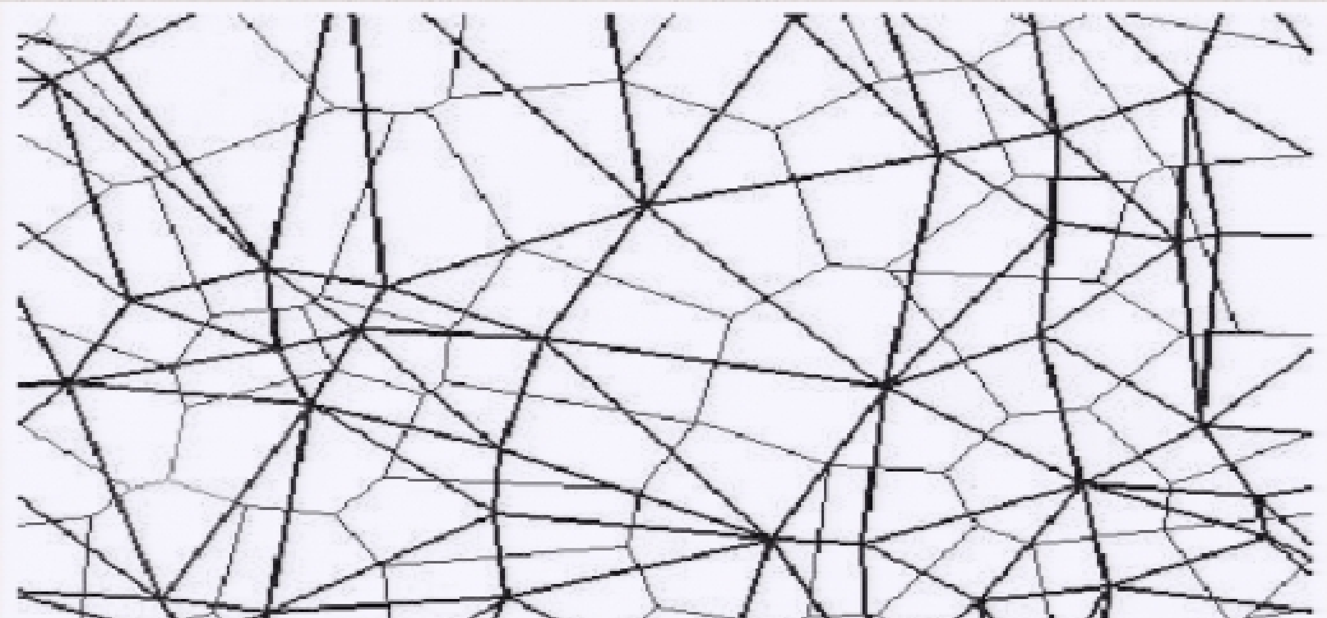
Γ is a dual spin-net of a random triangulation of q_{ab}.

$$\frac{<\Psi|\widehat{\sqrt{j(j+1)}}|\Psi>}{<\Psi|\hat{v}|\Psi>} = C = \pi^{4/3} \left(\frac{7^4 2^{20}}{3^5 5^2} \right)^{1/9}$$



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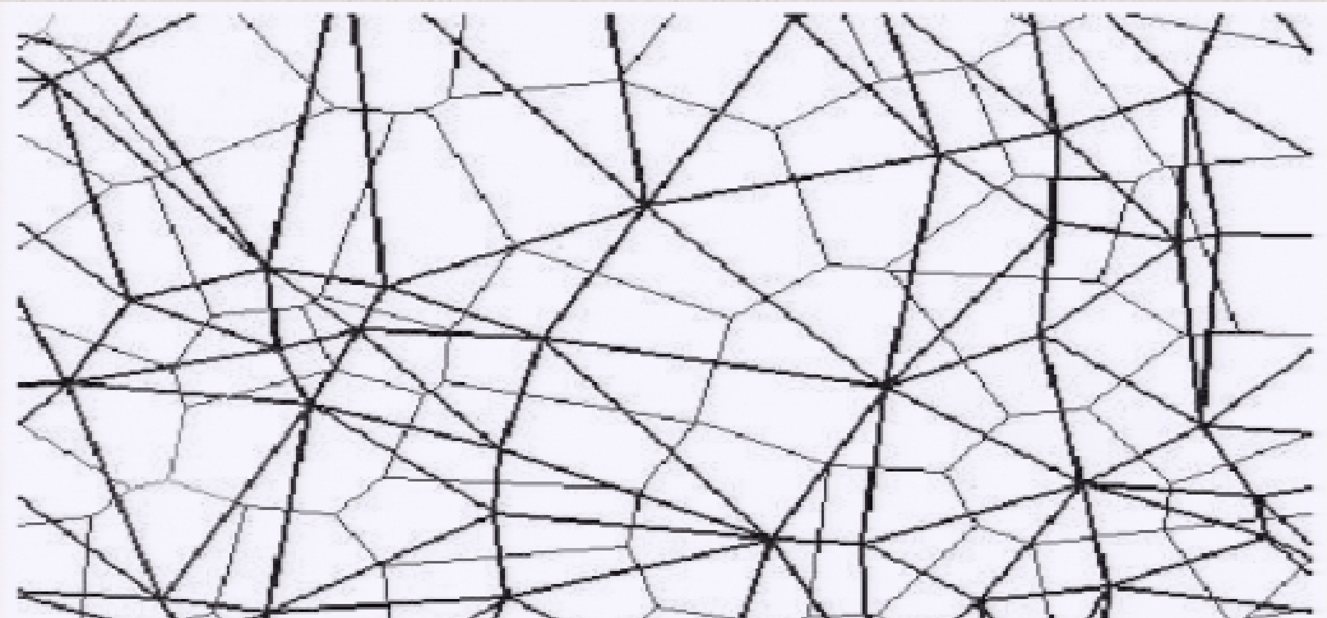

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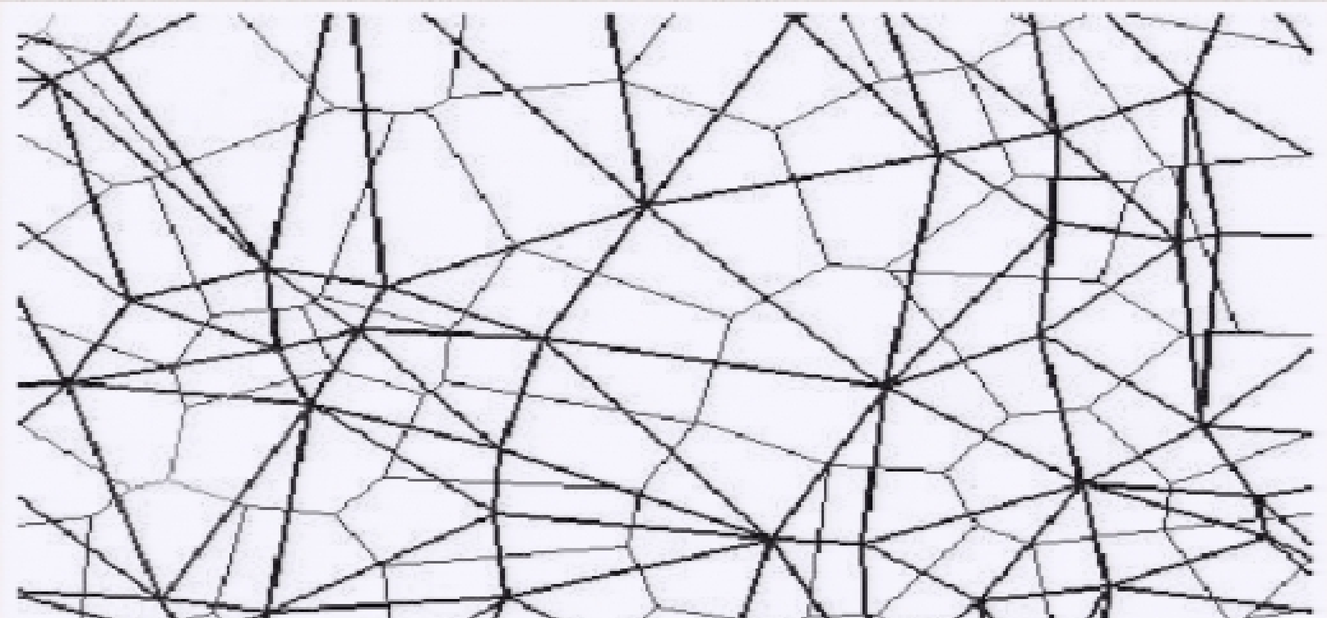

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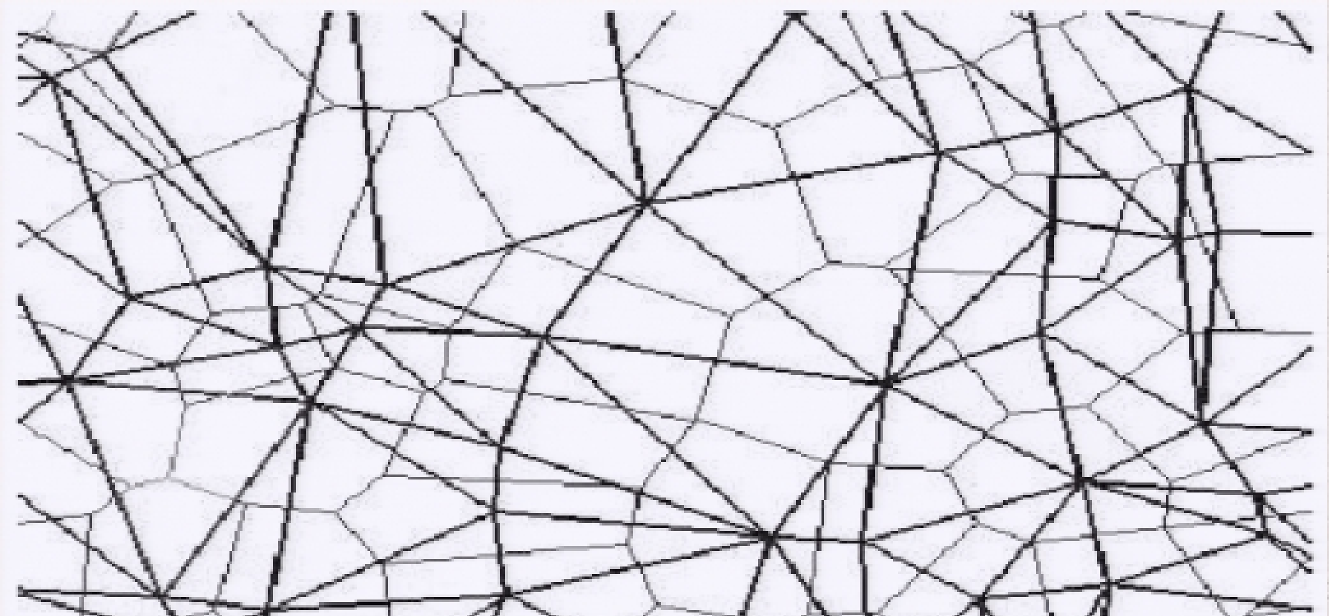


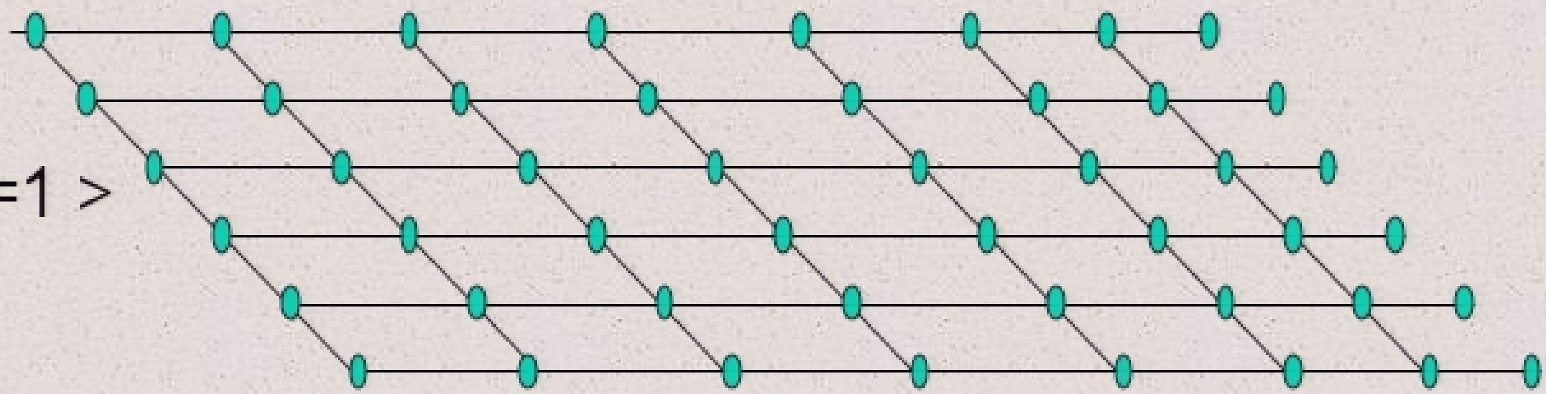
A simple solution: j=1, superposition of l=0, 1 2:

l: 0 1 2

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{4 3^{1/4}} - 1$$

$|\Gamma$, j=1,l=1 >



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Low energy fermions moving on Γ propagate as if they are in

A simple solution: j=1, superposition of l=0, 1 2:

l: 0 1 (green dot) 2 (red dot)

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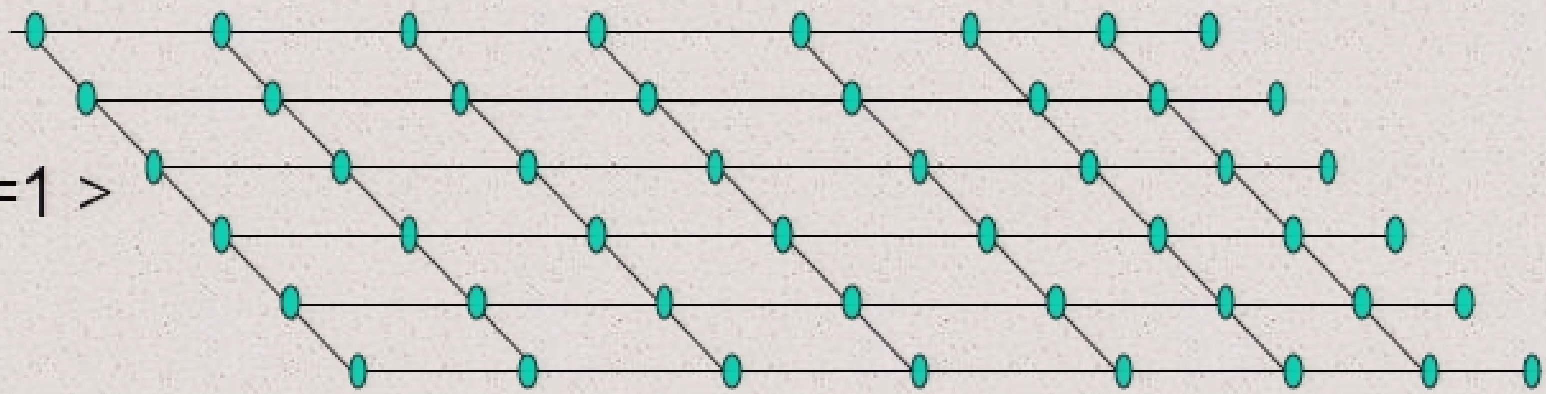

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Low energy fermions moving on Γ propagate as if they are in the continuum defined by q

A simple solution: j=1, superposition of l=0, 1 2:

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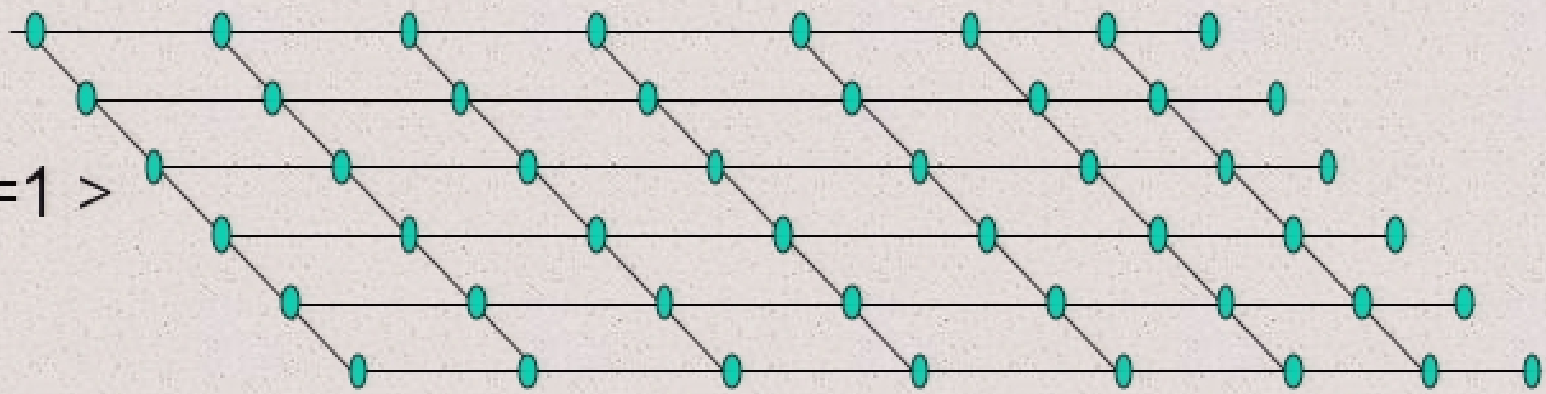

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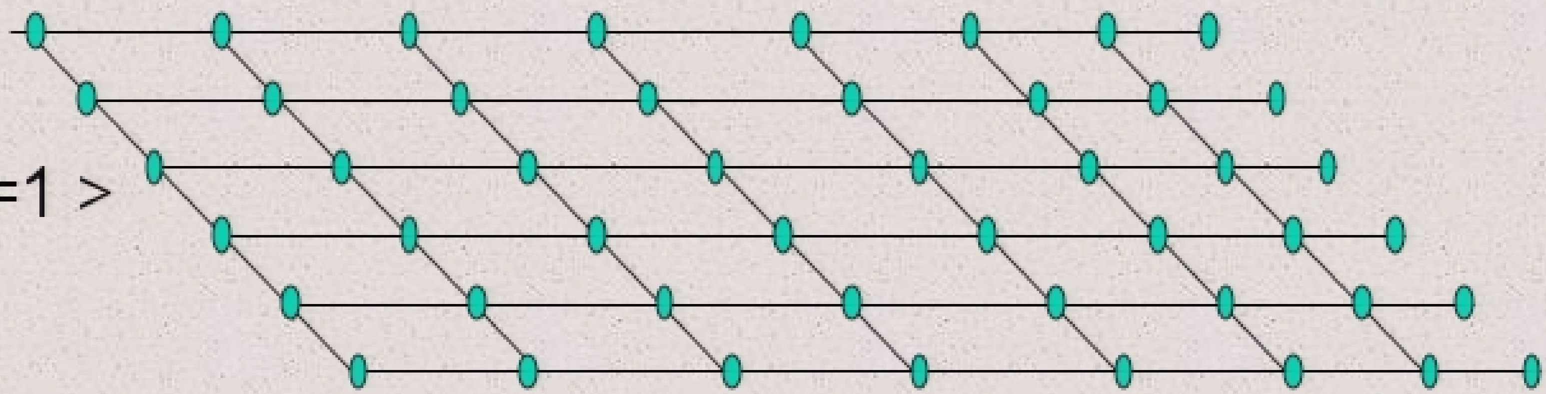

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Low energy fermions moving on Γ propagate as if they are in the continuum defined by q

A simple solution: j=1, superposition of l=0, 1 2:

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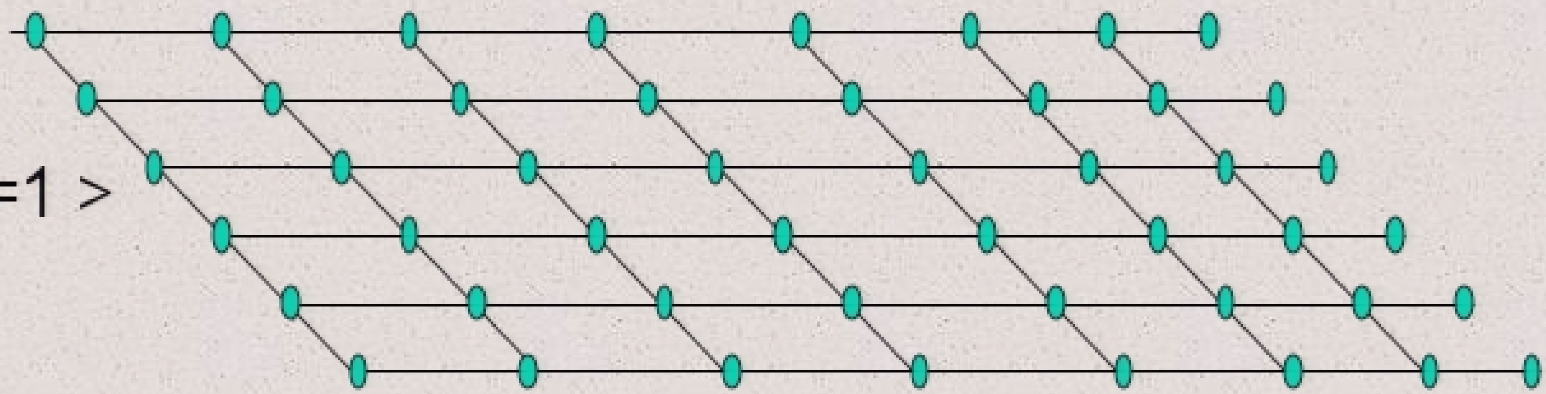

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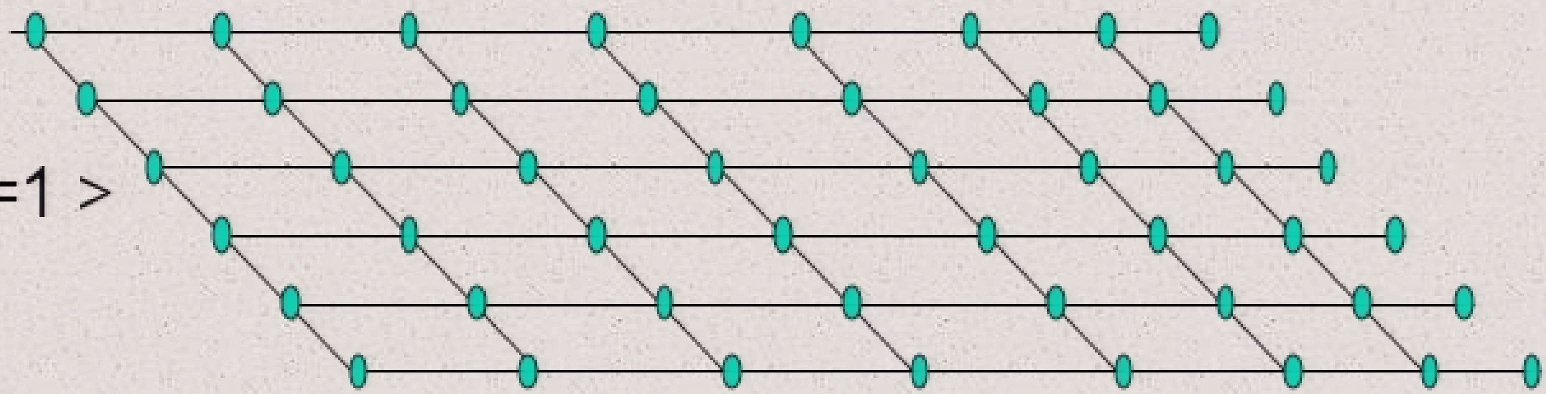

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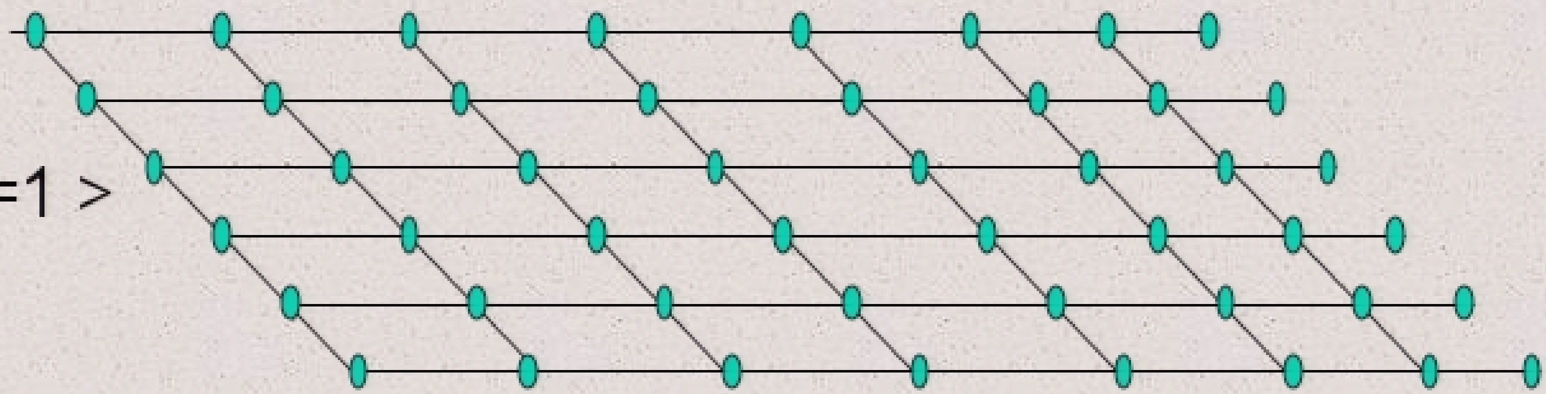

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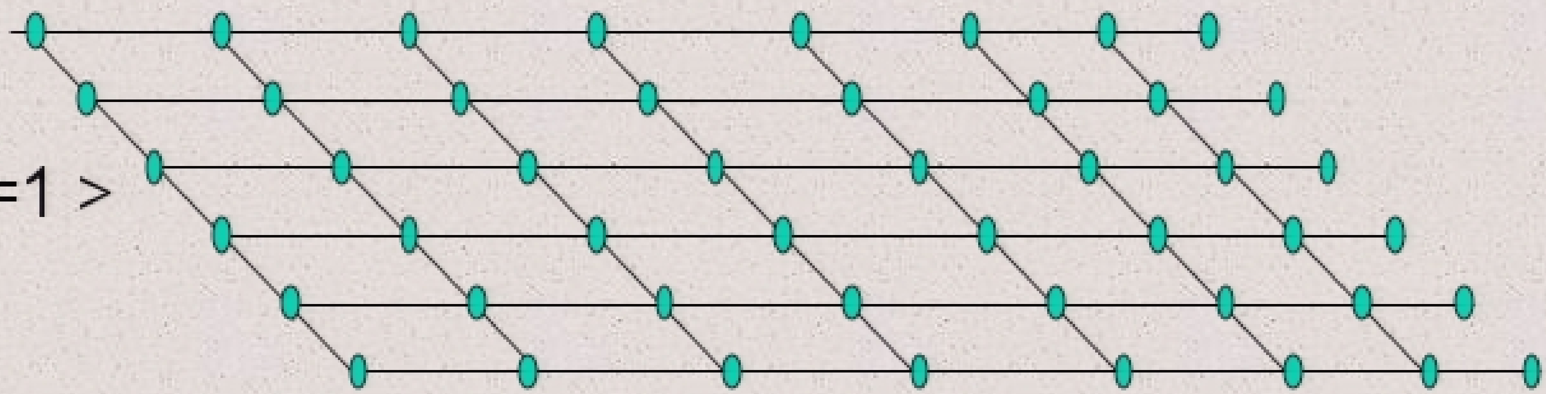

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Low energy fermions moving on Γ propagate as if they are in the continuum defined by q

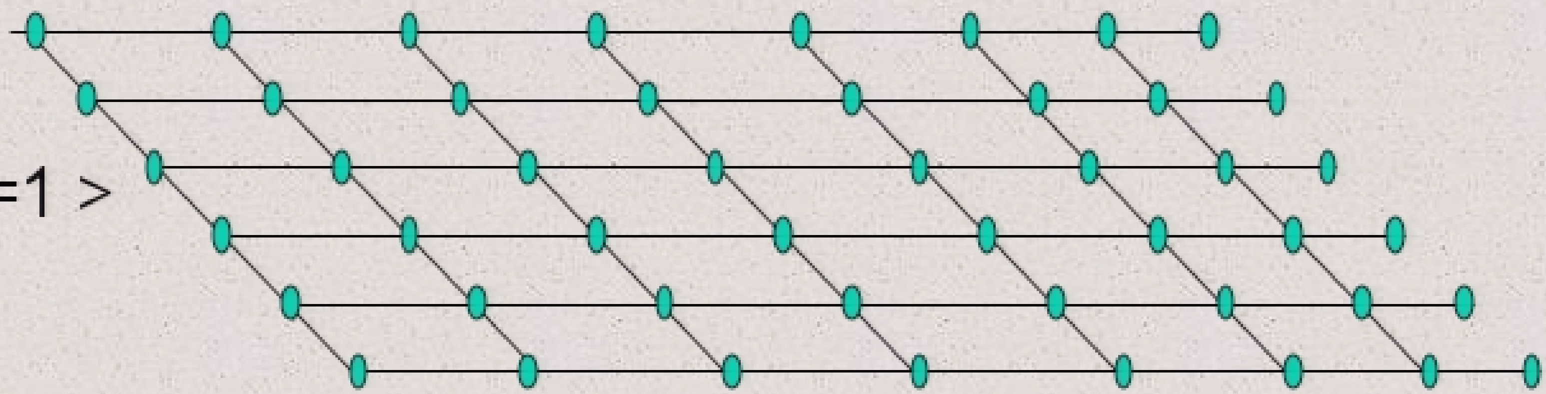
A simple solution: j=1, superposition of l=0, 1 2:

l: 0 1 2

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{43^{1/4}} - 1$$

$|\Gamma$, j=1,l=1 >



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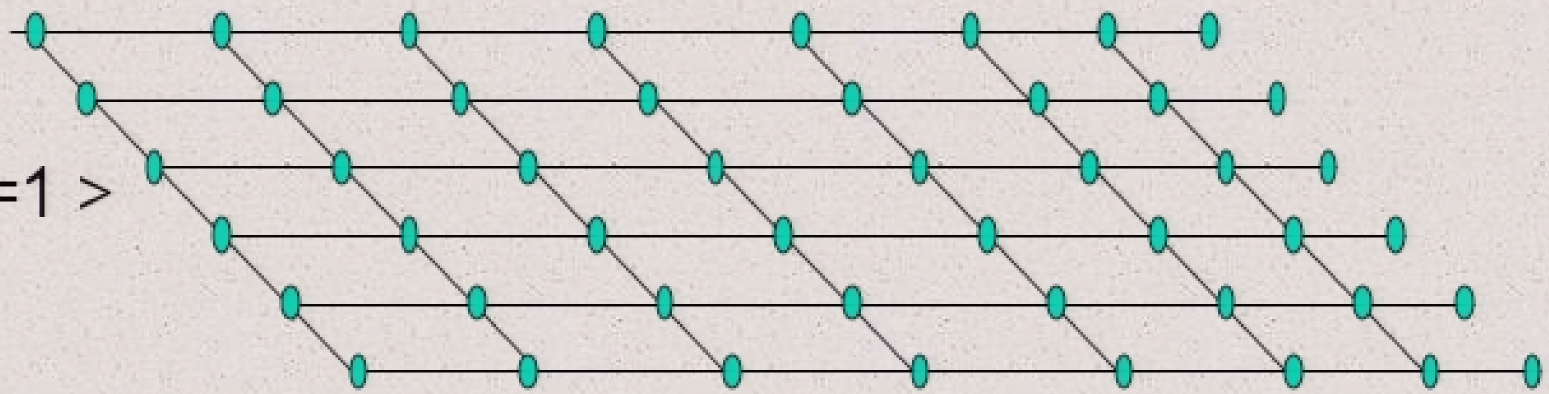

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Low energy fermions moving on Γ propagate as if they are in the continuum defined by q

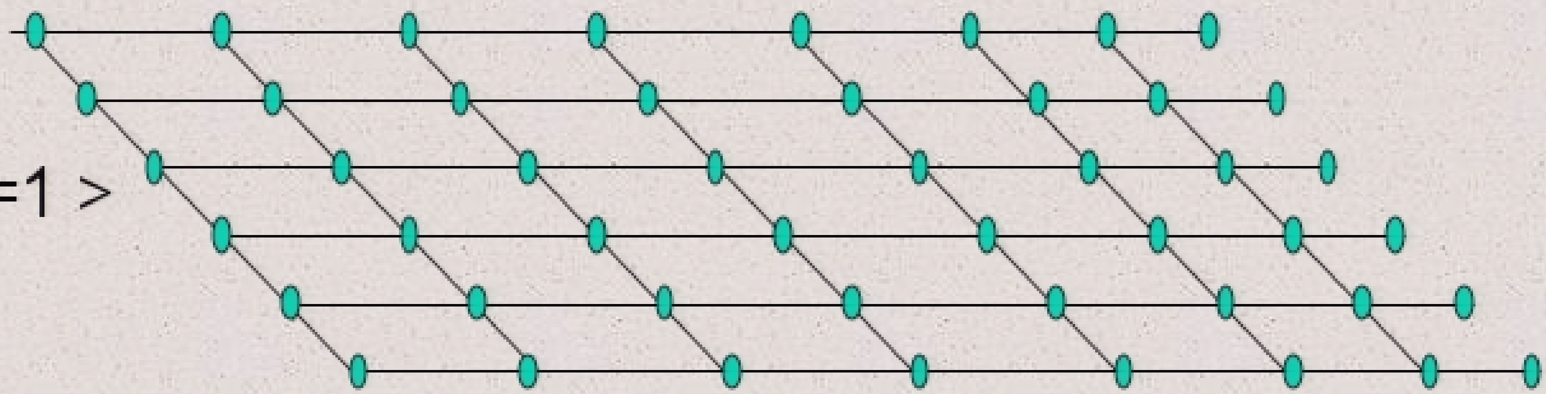
A simple solution: j=1, superposition of l=0, 1 2:

l: 0 1 (teal) 2 (orange)

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{43^{1/4}} - 1$$

$|\Gamma$, j=1,l=1 >



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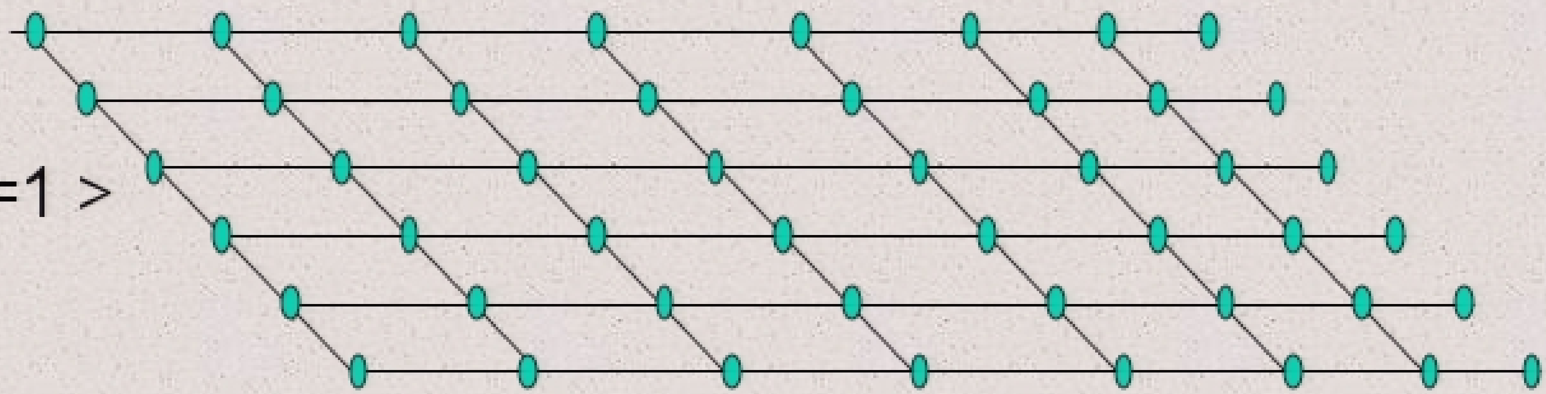

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Low energy fermions moving on Γ propagate as if they are in the continuum defined by q

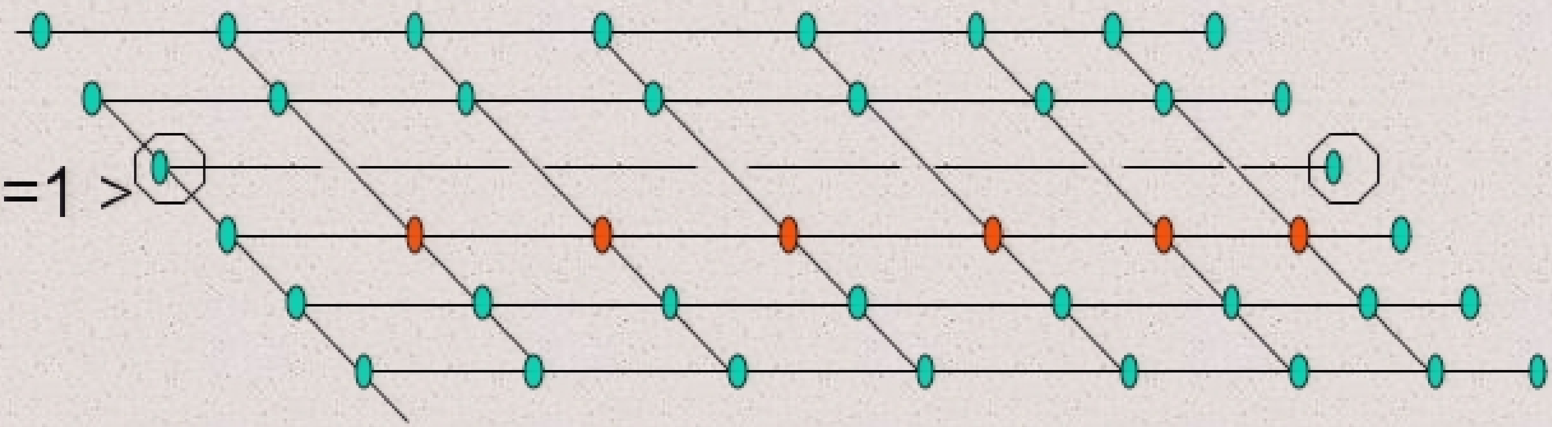
But a insert a non-local state for one of the components

l: 0 1 2

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{43^{1/4}} - 1$$

$|\Gamma', j=1, l=1 >$



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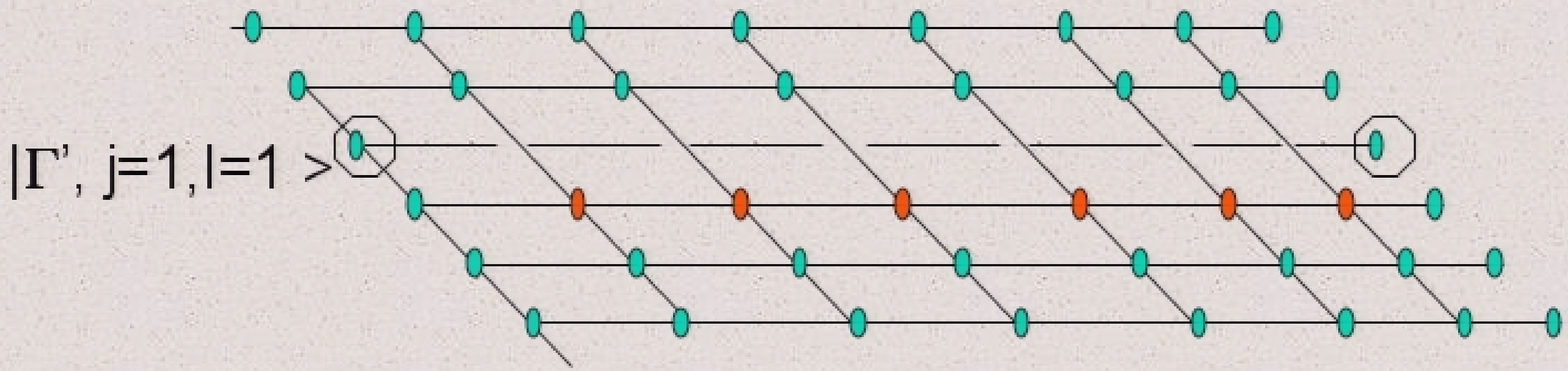
But a fermion moving on Γ' exhibits non-locality as two sites, distant in q , are connected by a link

But a insert a non-local state for one of the components

l: 0 1 • 2 •

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{43^{1/4}} - 1$$



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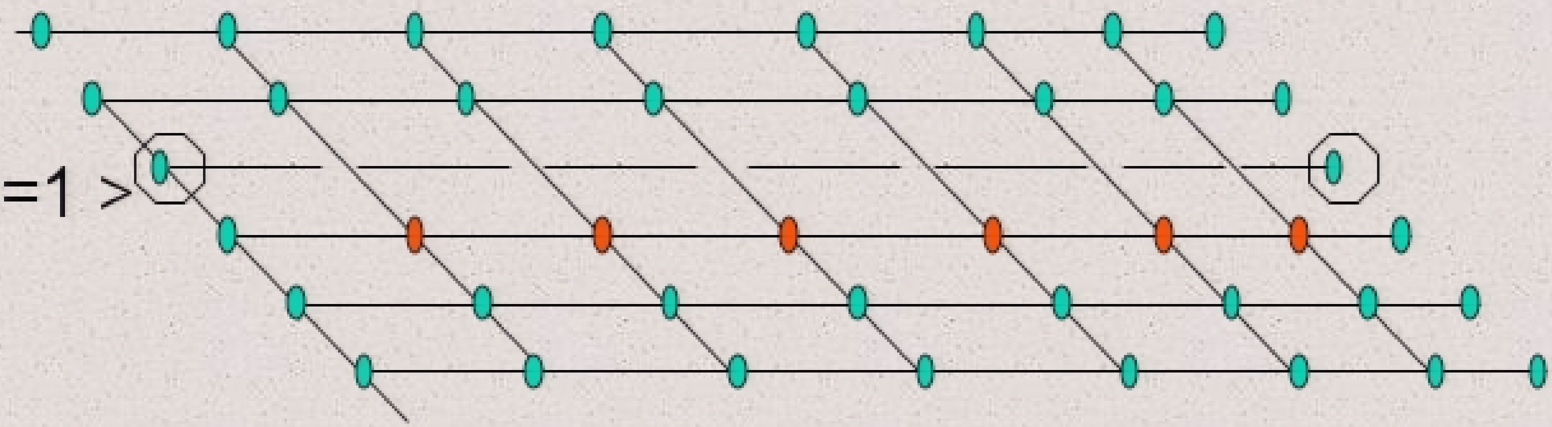
$|\Gamma', j=1, l=1 >$



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But a fermion moving on Γ' exhibits non-locality as two sites, distant in q , are connected by a link

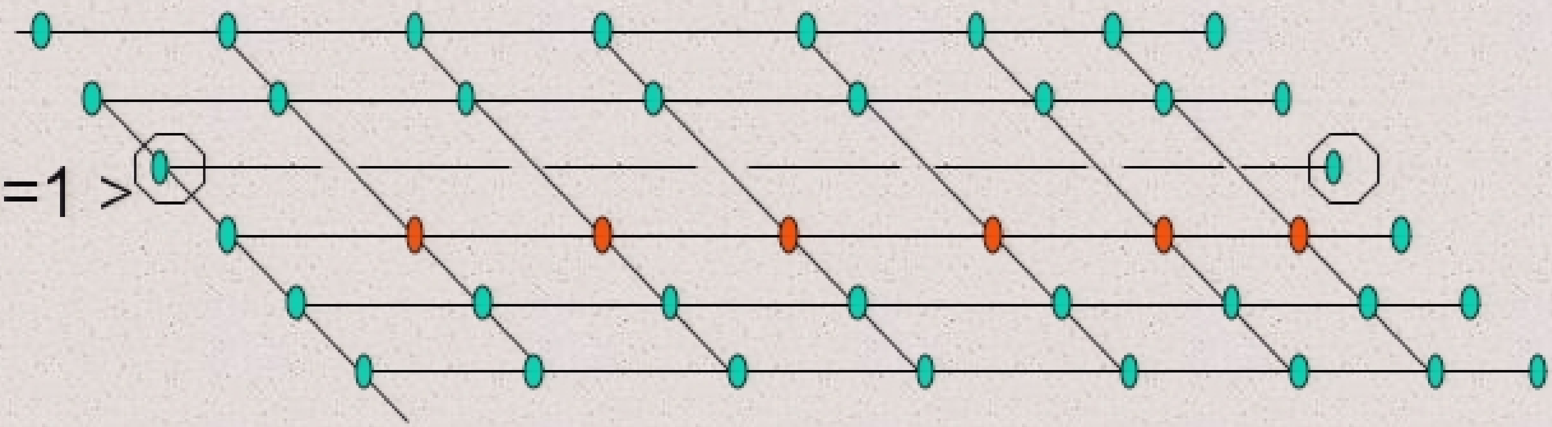
But a insert a non-local state for one of the components

l: 0 1 (teal dot) 2 (orange dot)

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{4 3^{1/4}} - 1$$

$|\Gamma', j=1, l=1>$



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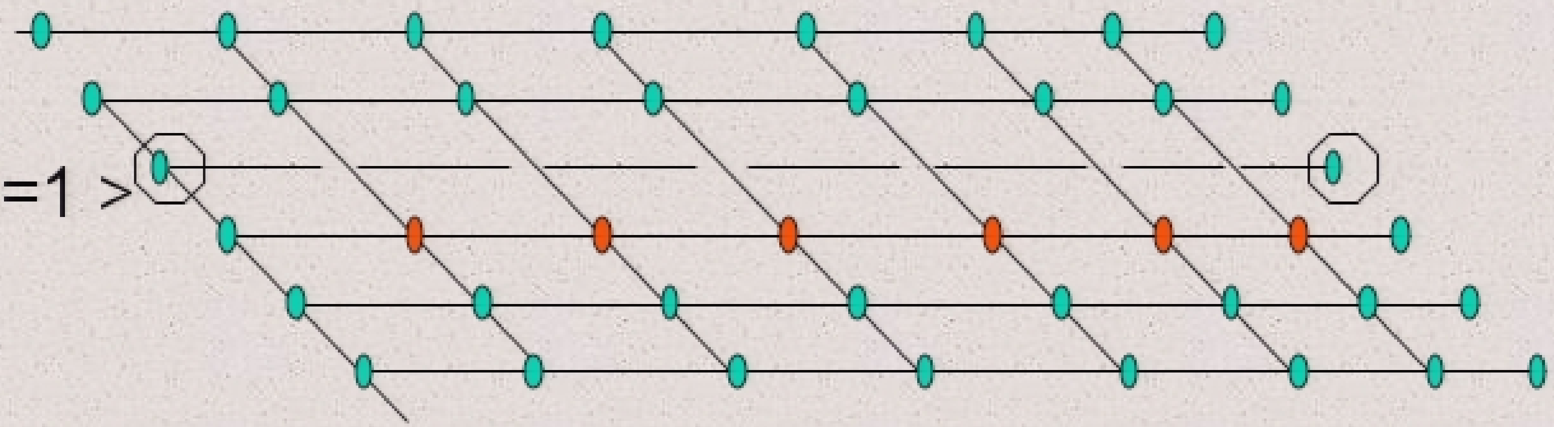

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But a fermion moving on Γ' exhibits non-locality as two sites, distant in q , are connected by a link

But a insert a non-local state for one of the components

l: 0 1 2

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{4 3^{1/4}} - 1$$

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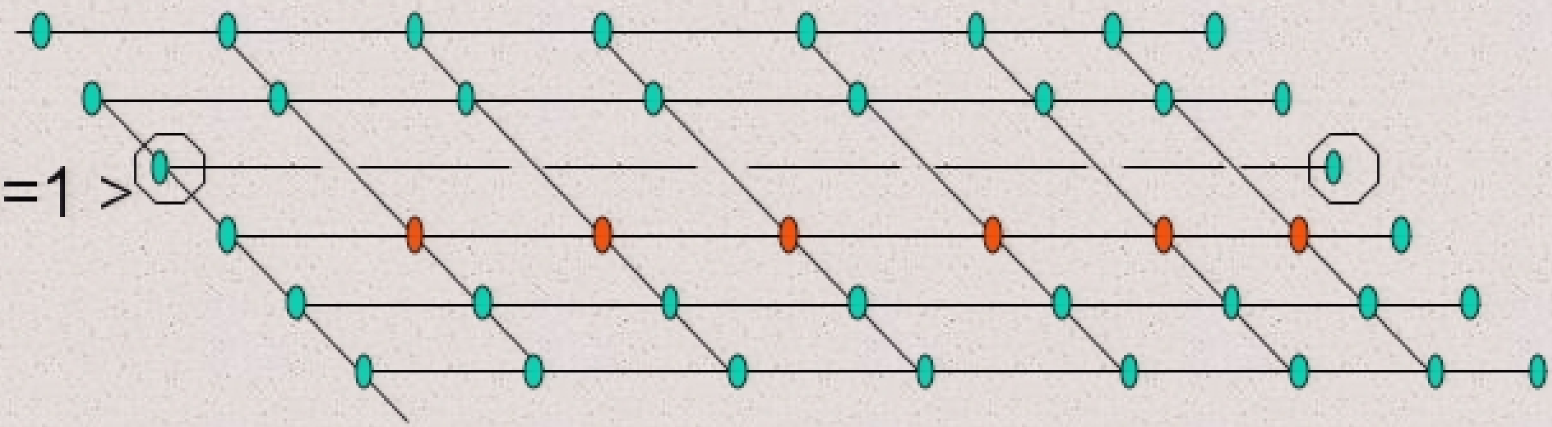

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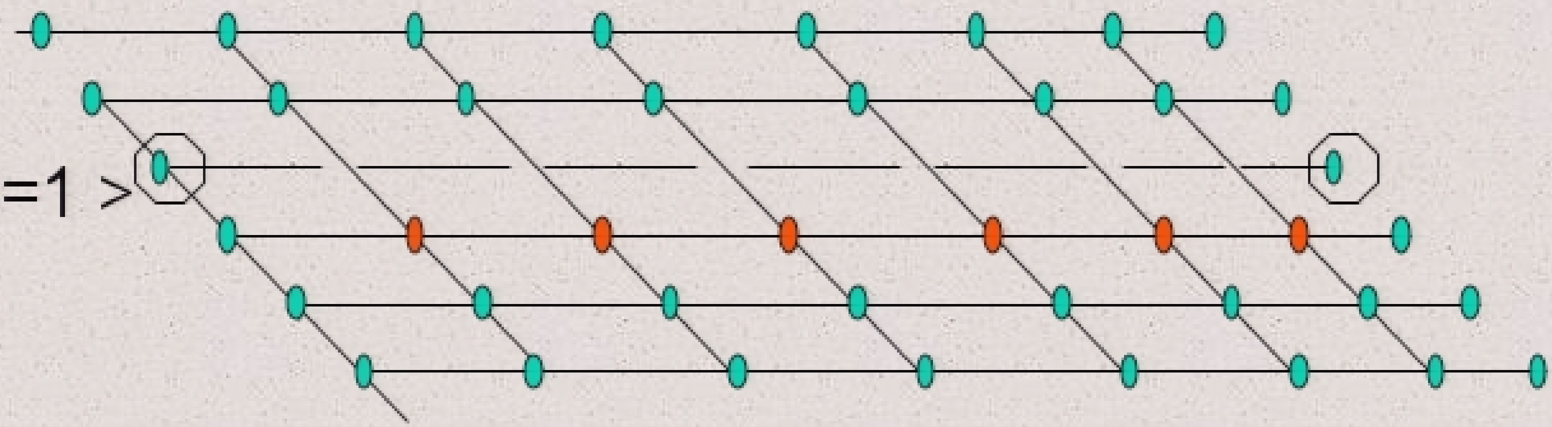
But a insert a non-local state for one of the components

l: 0 1 2

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{43^{1/4}} - 1$$

$|\Gamma', j=1, l=1>$



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But a fermion moving on Γ' exhibits non-locality as two sites, distant in q , are connected by a link

But a insert a non-local state for one of the components

l: 0 1 (teal dot) 2 (orange dot)

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{43^{1/4}} - 1$$

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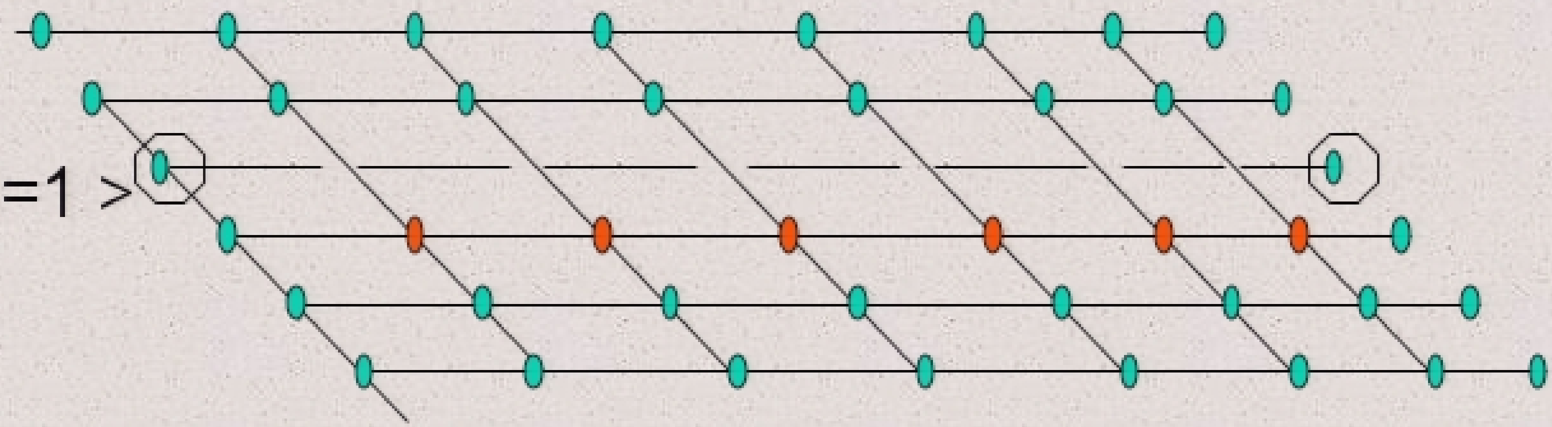

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l: 0 1 (teal dot) 2 (orange dot)

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{43^{1/4}} - 1$$

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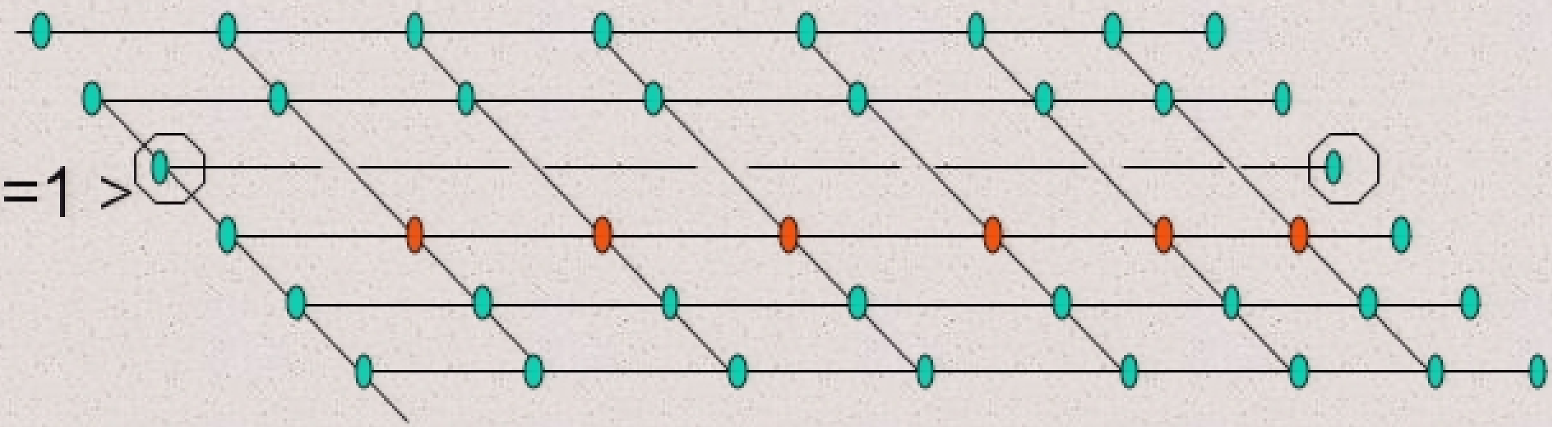

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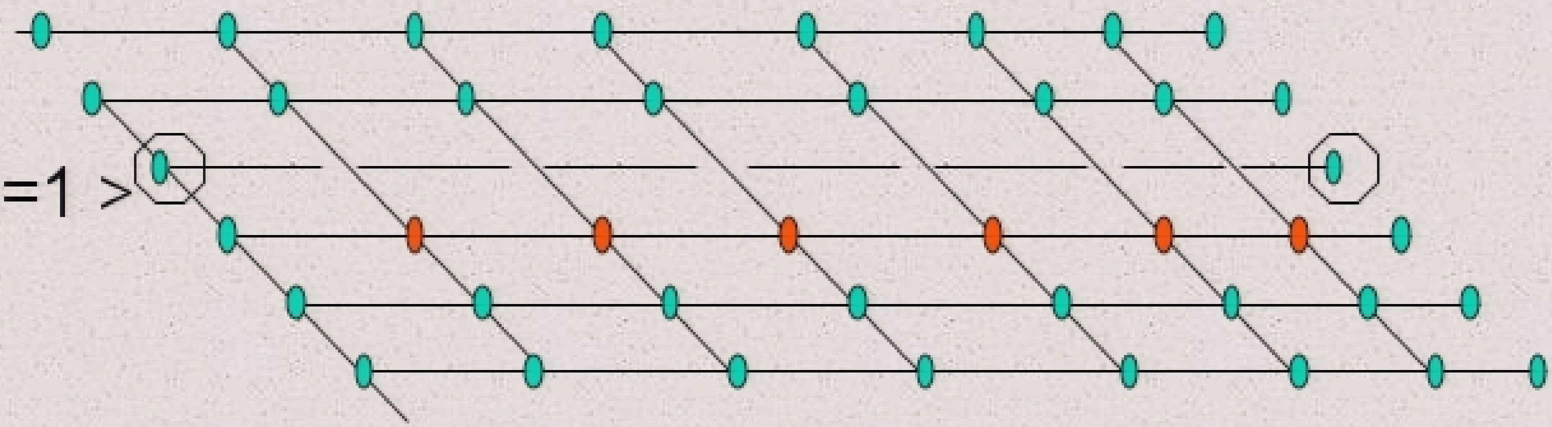
But a insert a non-local state for one of the components

l: 0 1 (green) 2 (orange)

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{43^{1/4}} - 1$$

$|\Gamma', j=1, l=1 >$



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But a insert a non-local state for one of the components

l: 0 1 2

v: $0 \quad 3^{1/4}/4 \quad 3^{1/4}/2$

$$\frac{|a_{1,0}|^2}{|a_{1,1}|^2} = \frac{C}{43^{1/4}} - 1$$

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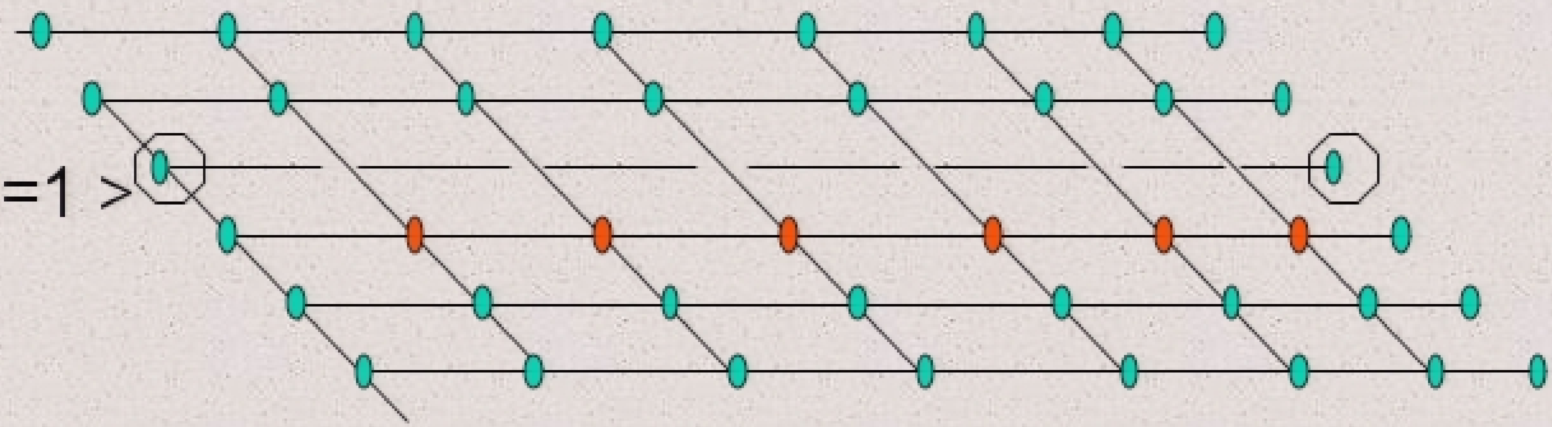

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v: 0 $3^{1/4}/4$ $3^{1/4}/2$

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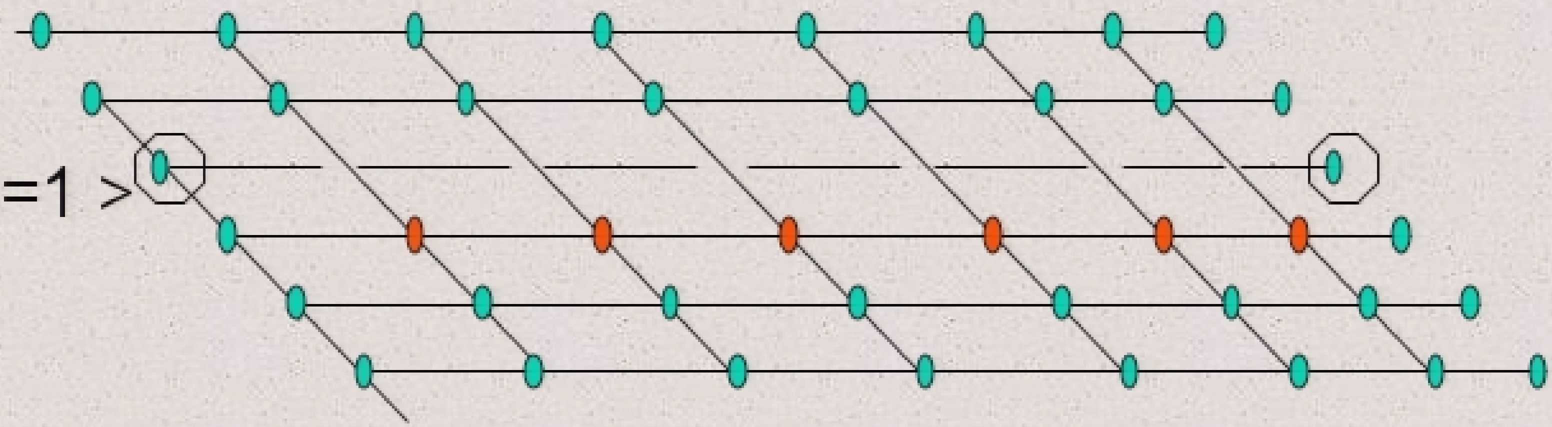

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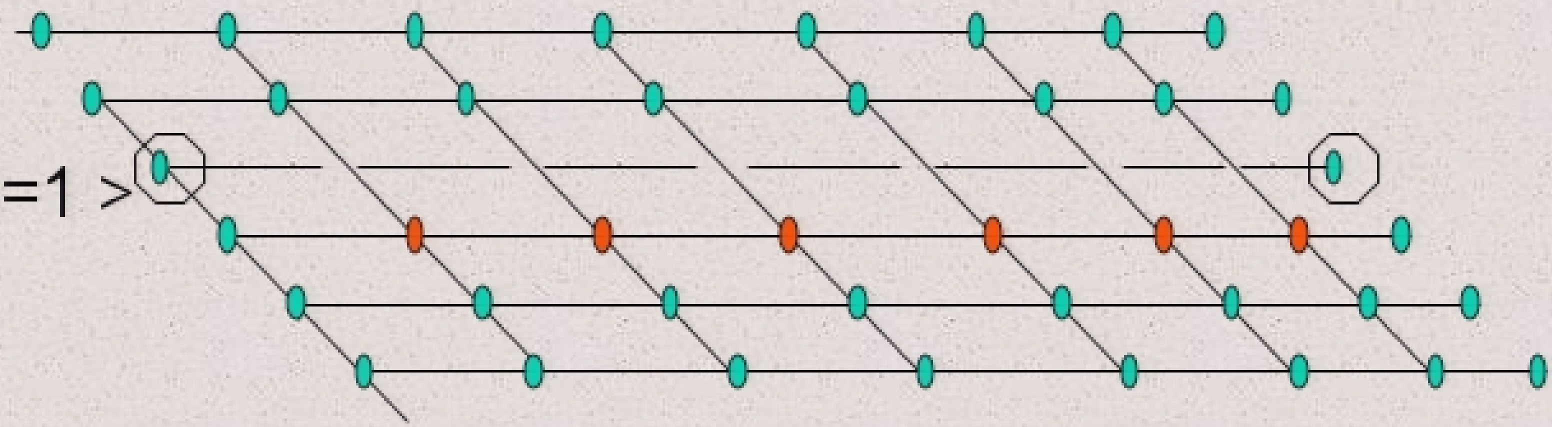

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l: 0 1 ● 2 ●

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

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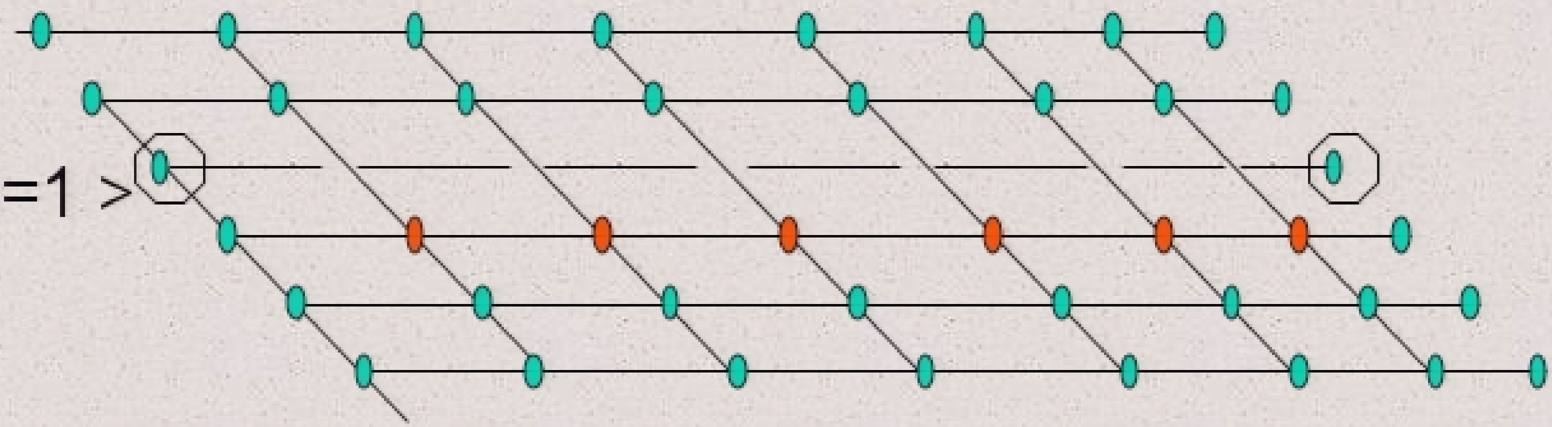

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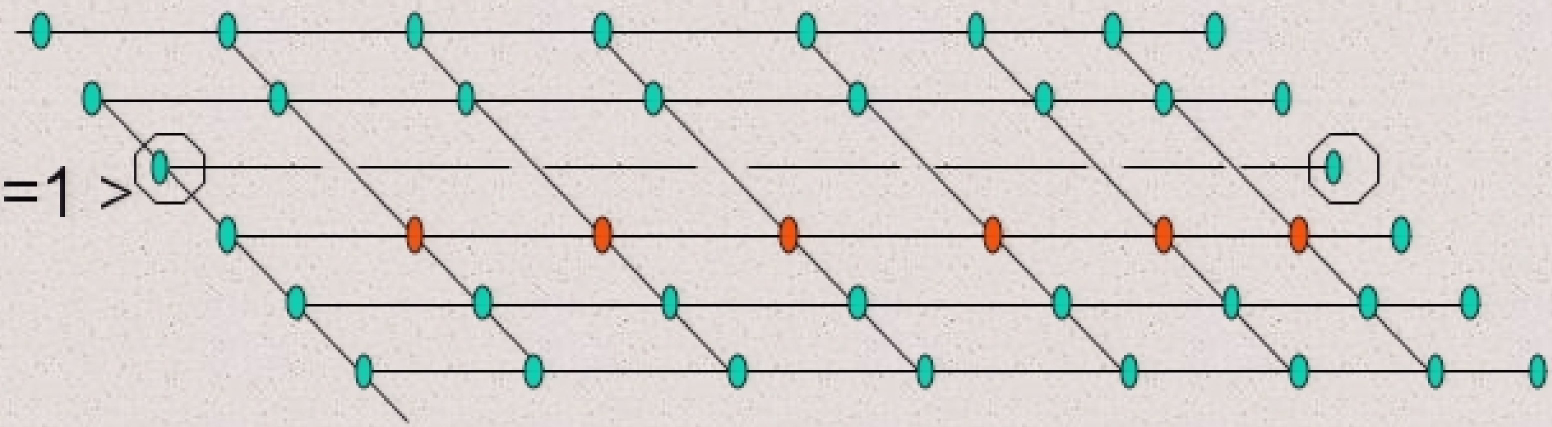

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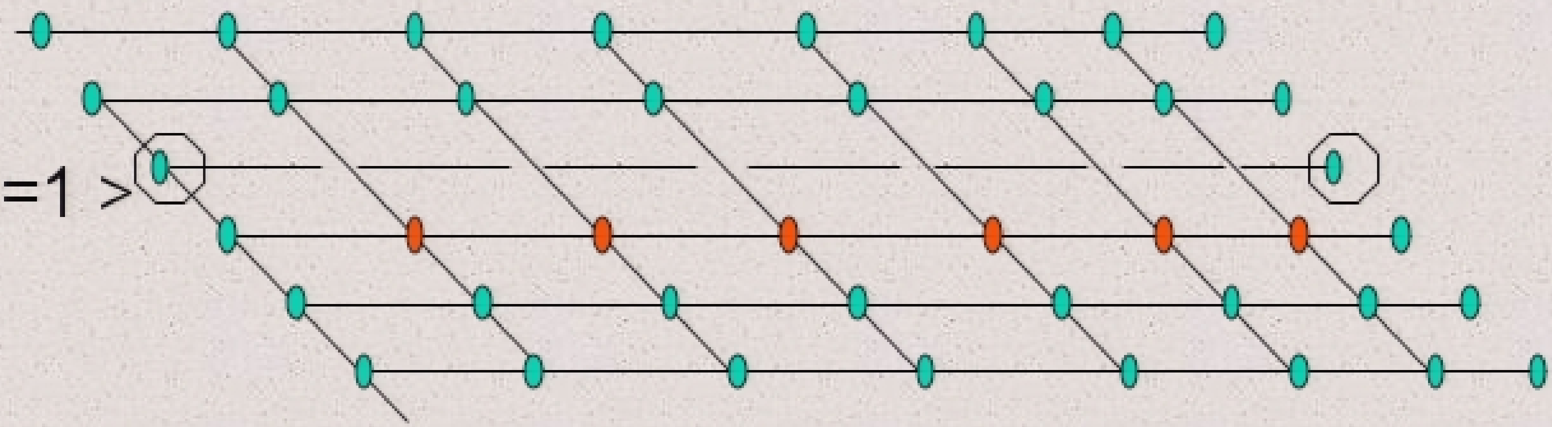

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l: 0 1 • 2 •

v: 0 $3^{1/4}/4$ $3^{1/4}/2$

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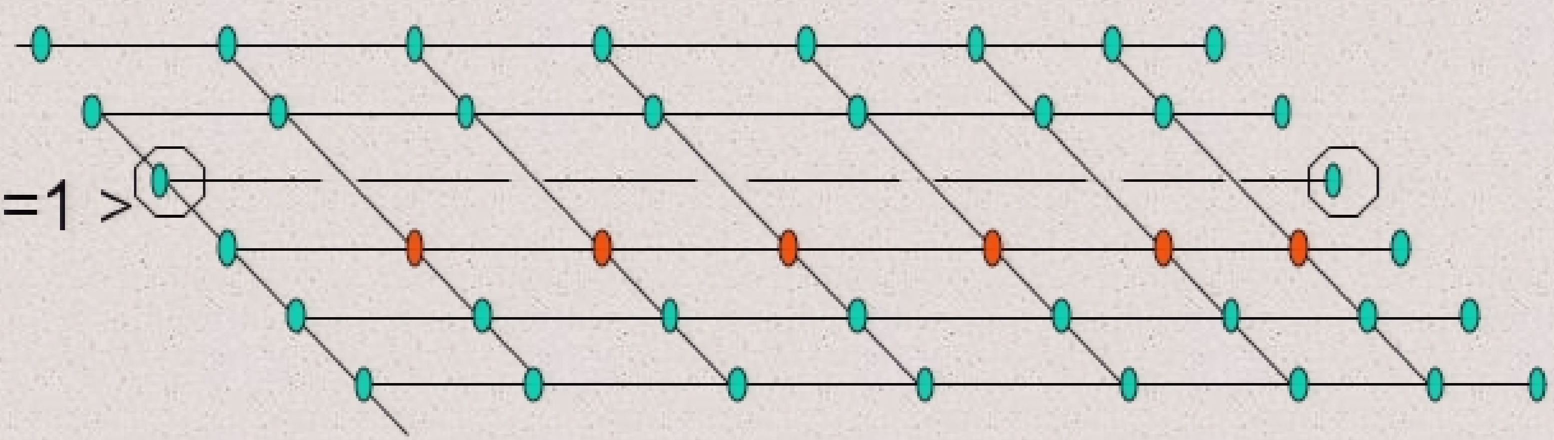

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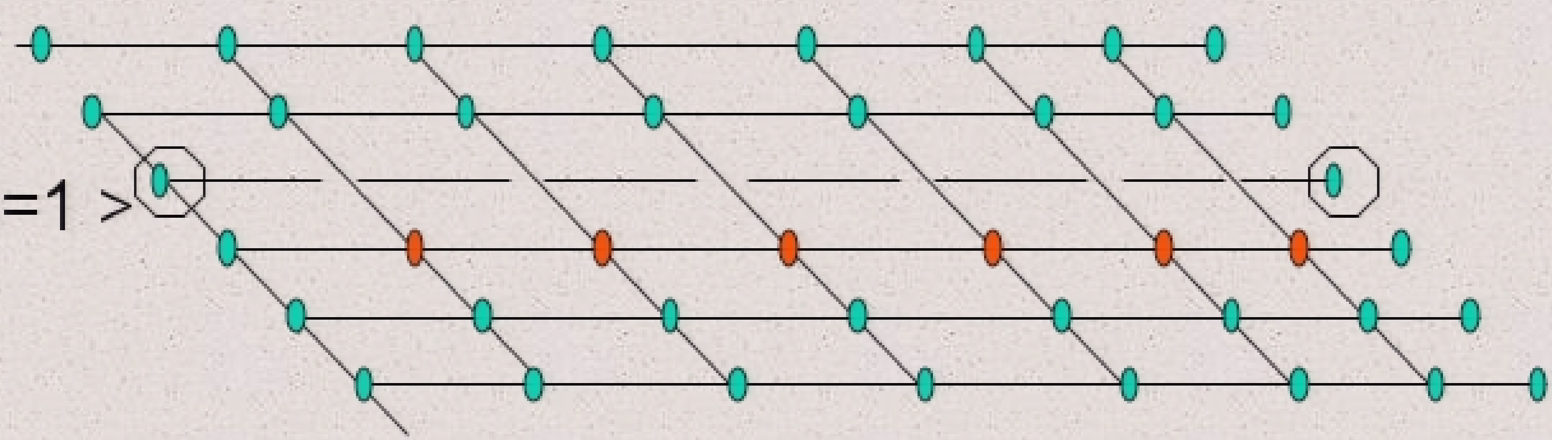

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So the weave conditions do not imply locality.

There seems nothing that guarantees that microscopic locality defined by the connectivity of a given spinnet goes over into locality of a semiclasical or coherent state from which classial geometry would emerge.

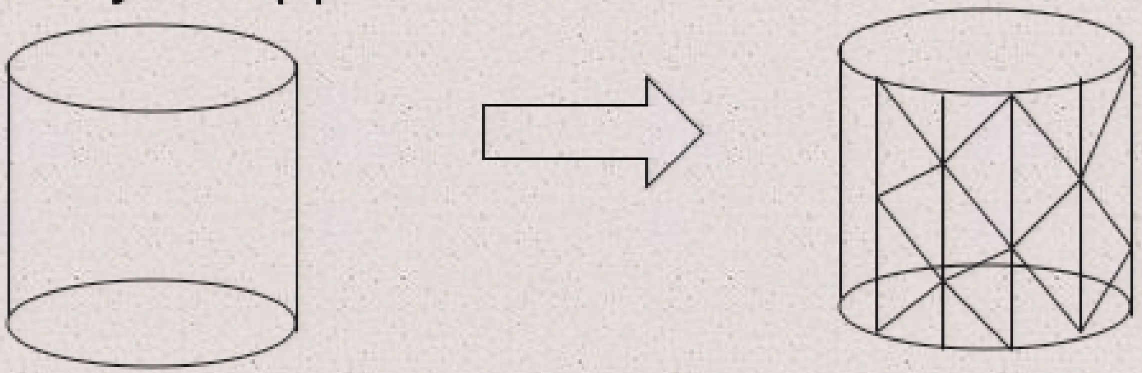
Similarly there is nothing that seems to guarantee that causality of spin foams goes over to causal structure of classical spacetime in the low energy limit.

Furthermore, there is a problem suppressing non-local links, as there are potentially so many more of them.

This is the inverse problem.

The inverse problem for discrete spacetimes:

Its easy to approximate smooth fields with discrete structures.



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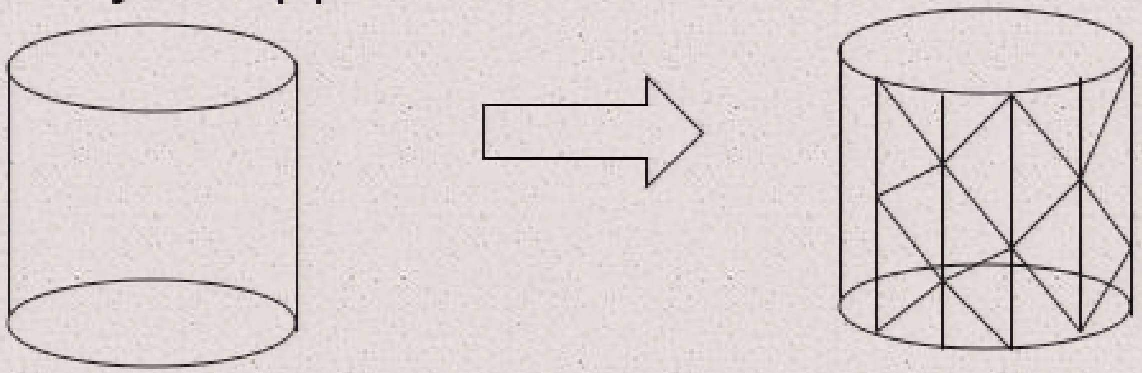

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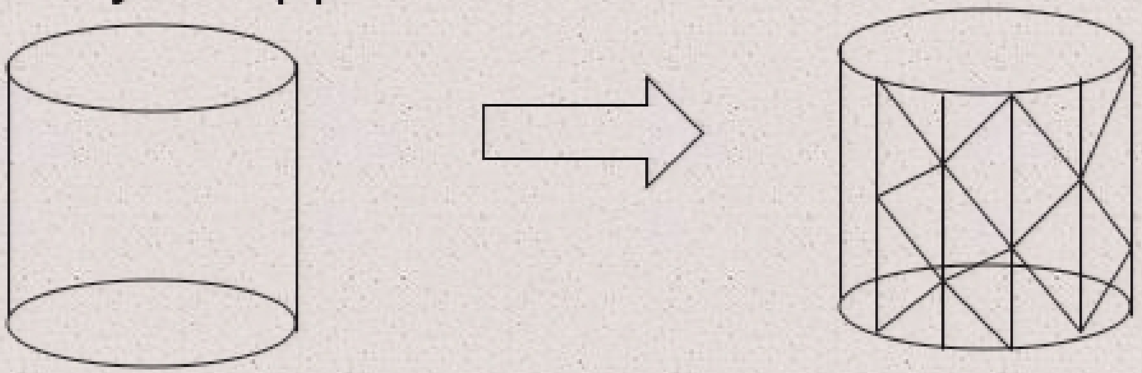

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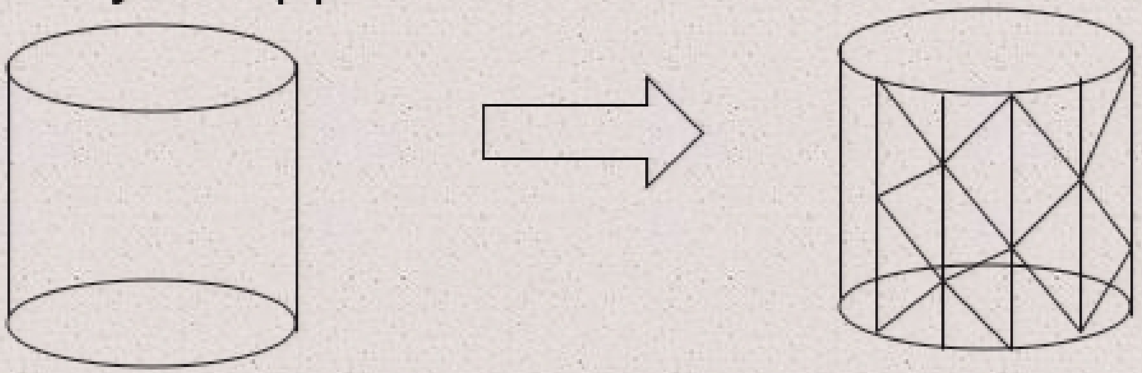
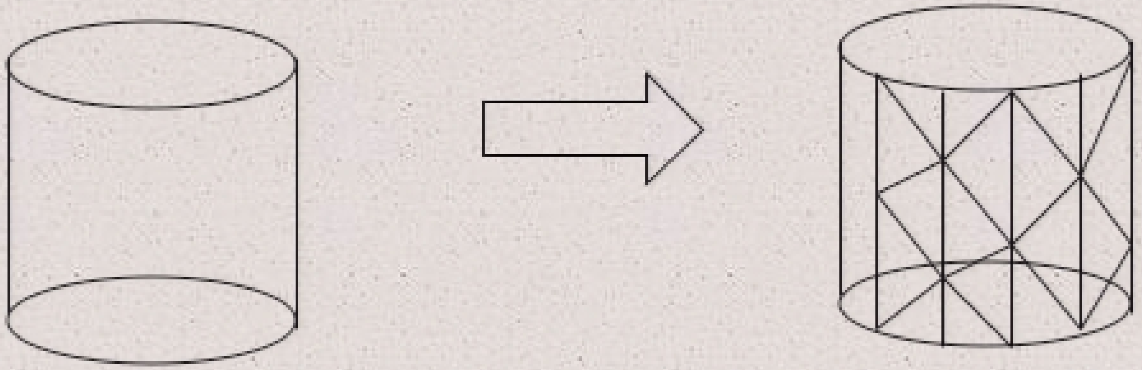
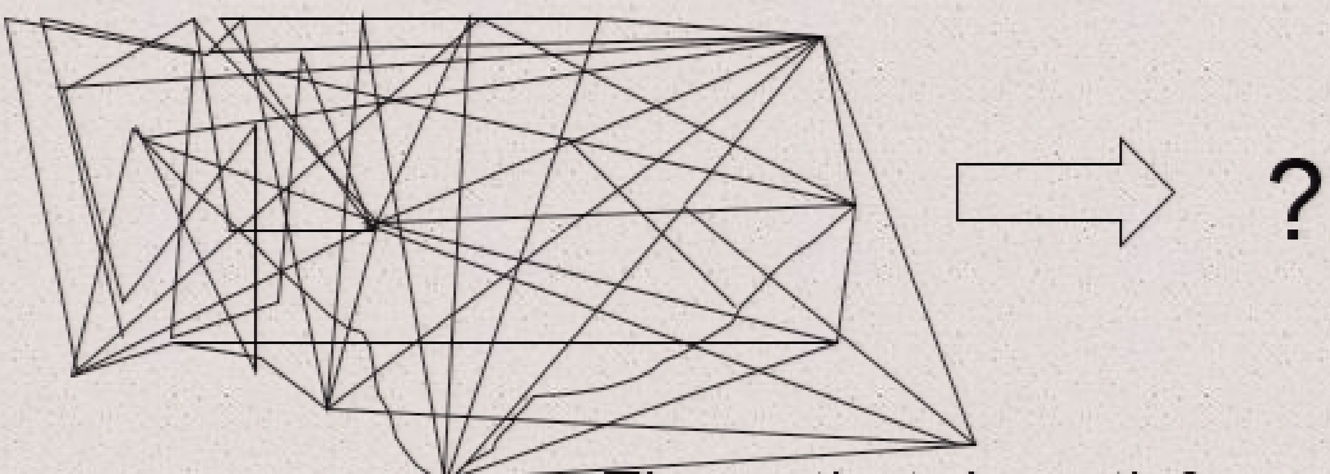


The inverse problem for discrete spacetimes:

Its easy to approximate smooth fields with combinatoric structures.



But generic graphs do not embed in manifolds of low dimension, preserving even approximate distances.



Those that do satisfy constraints unnatural in the discrete context

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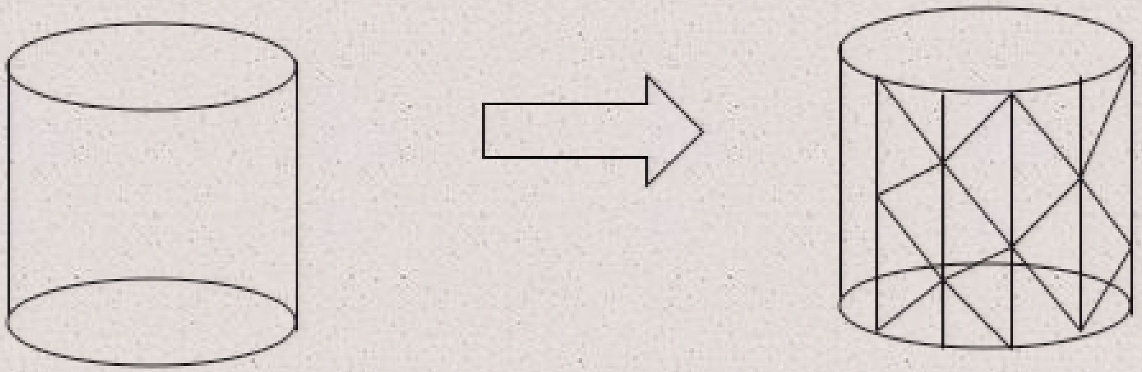

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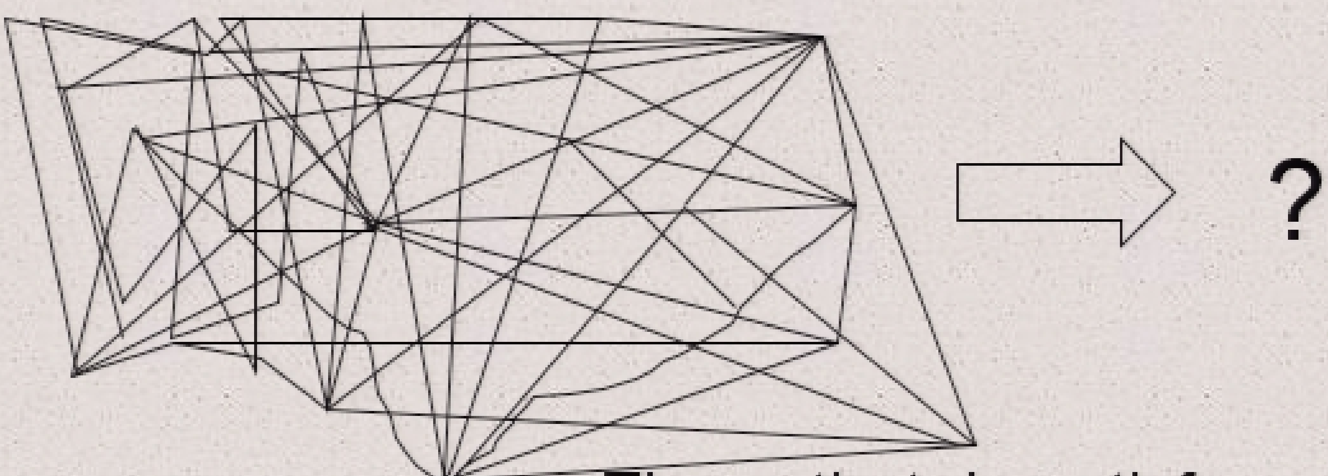

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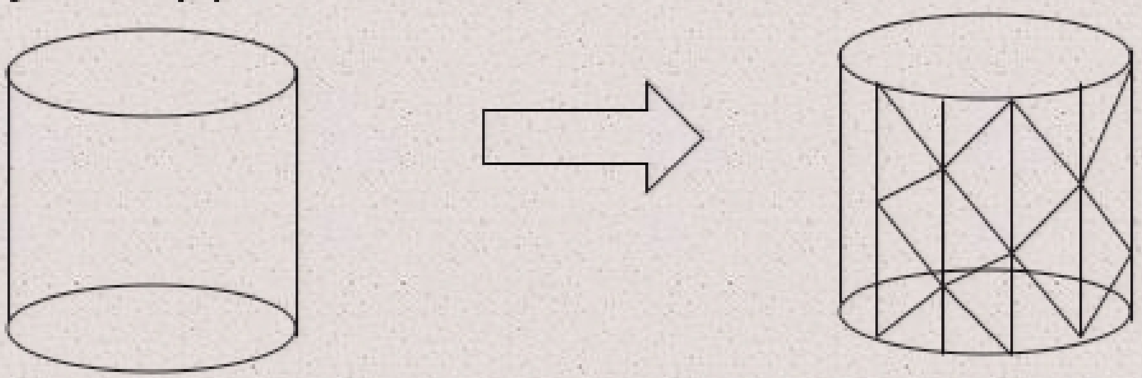

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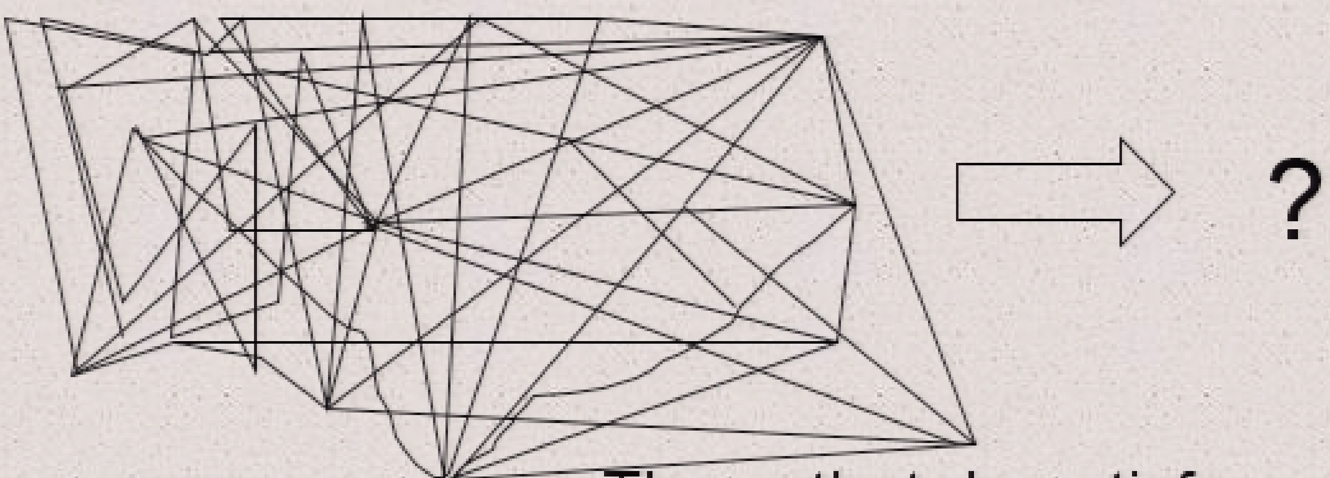

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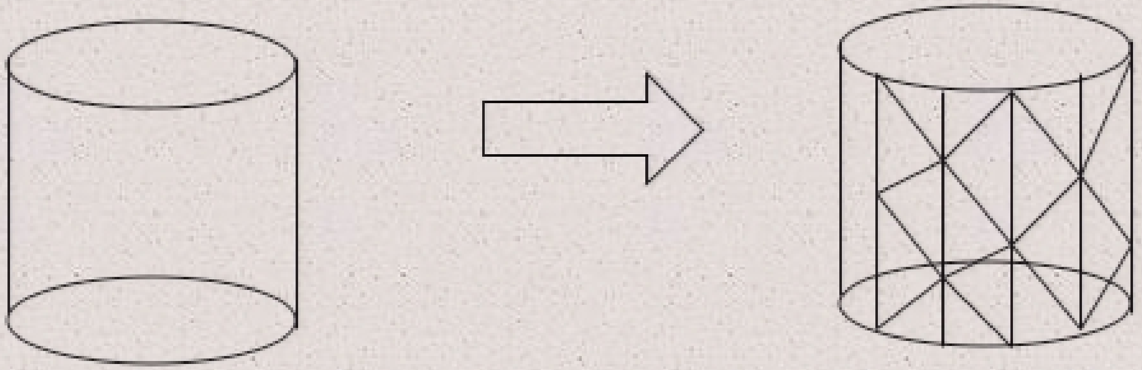

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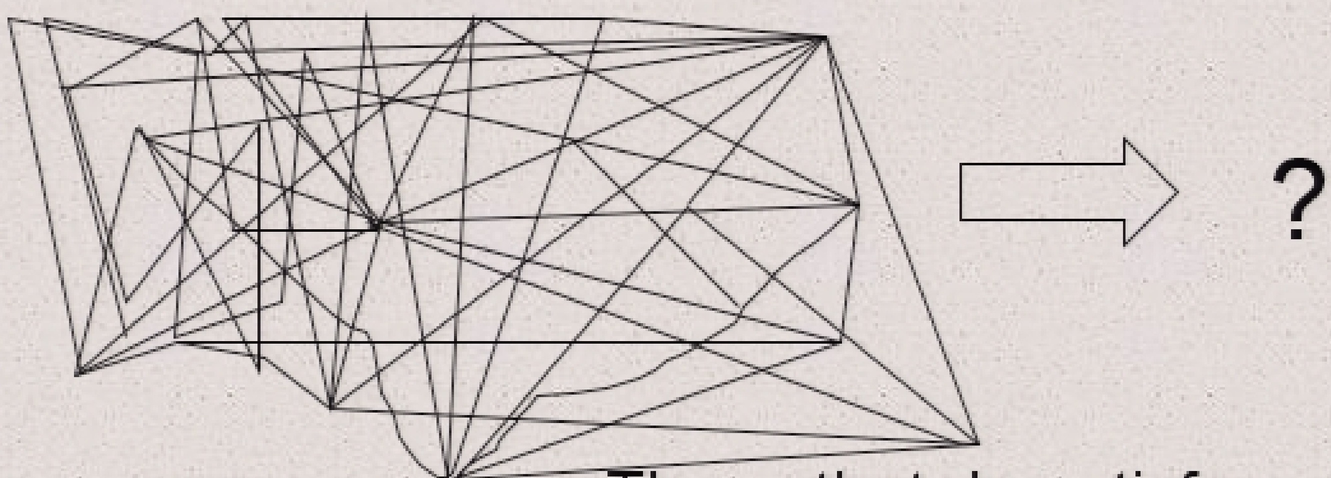
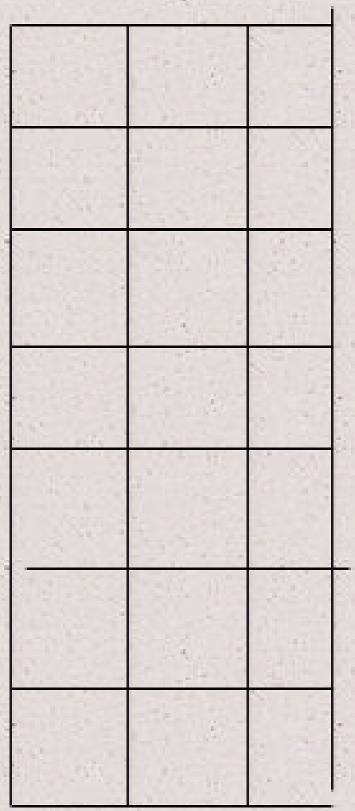


Those that do satisfy constraints unnatural in the discrete context

If locality is an emergent property of graphs, it is unstable:

Γ: a graph with N nodes that has only links local in an embedding (or whose dual is a good manifold triangulation) in d dimensions.



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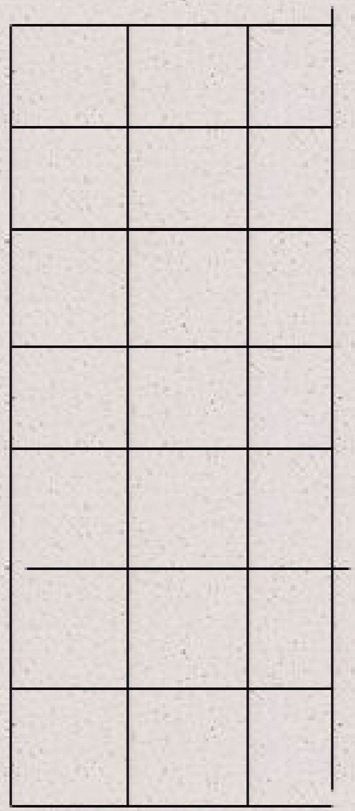


If locality is an emergent property of graphs, it is unstable:

Γ: a graph with N nodes that has only links local in an embedding (or whose dual is a good manifold triangulation) in d dimensions.

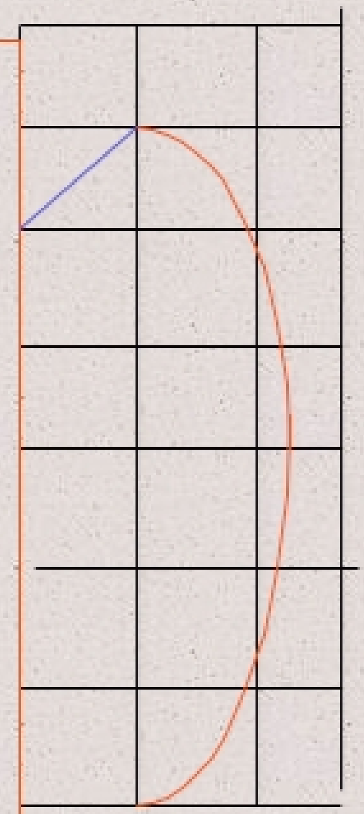
Lets add one more link randomly.

Does it conflict with the locality of the embedding?

d N ways that don't.

N^2 ways that do.

Thus, if the low energy definition of locality comes from a coarse graining of a combinatorial graph, it will be easily violated in fluctuations.



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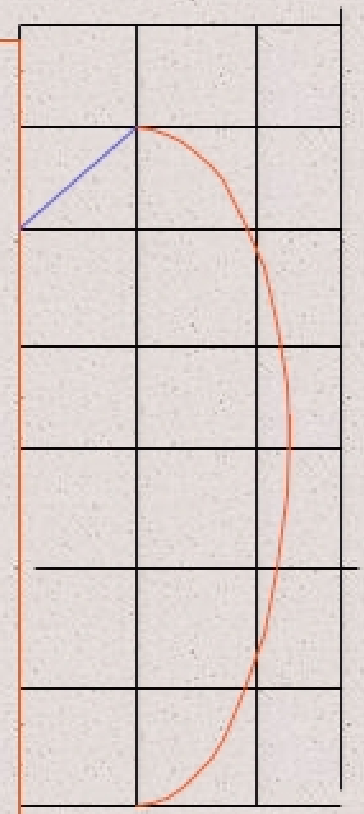

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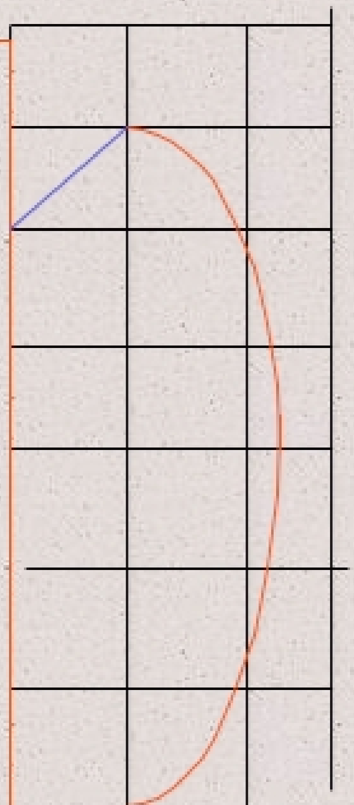

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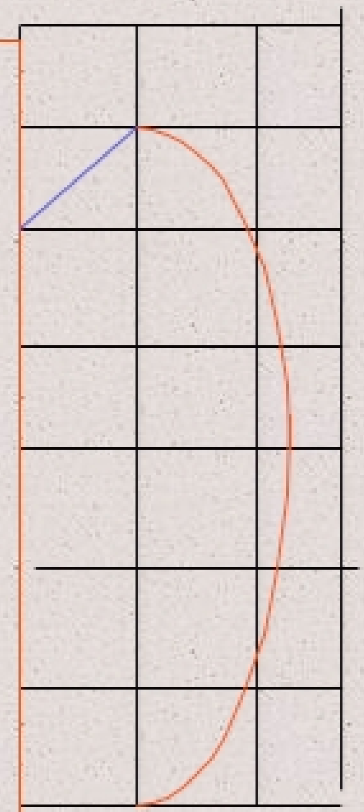

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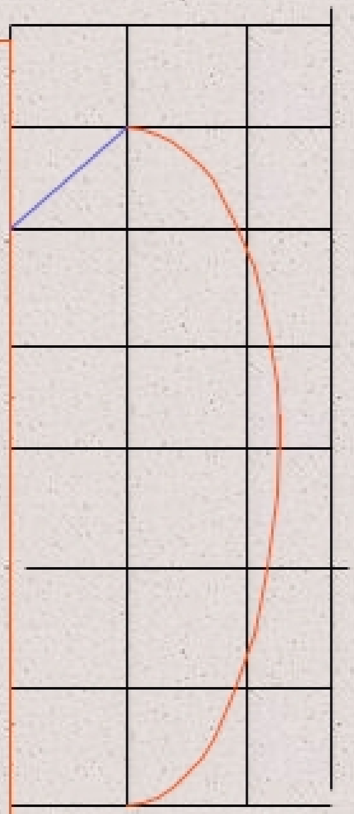

Other research programs have their own versions of inverse problems:

- Causal sets

  It is easy to approximate a classical spacetime by a causal set.

  But, almost no causal set approximates a low dimensional classical spacetime.

- Dynamical triangulations: same problem, most random triangulations define a low dimensional manifold with low haussdorf dimension.

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What are we to do about the inverse problem and the locality problem?

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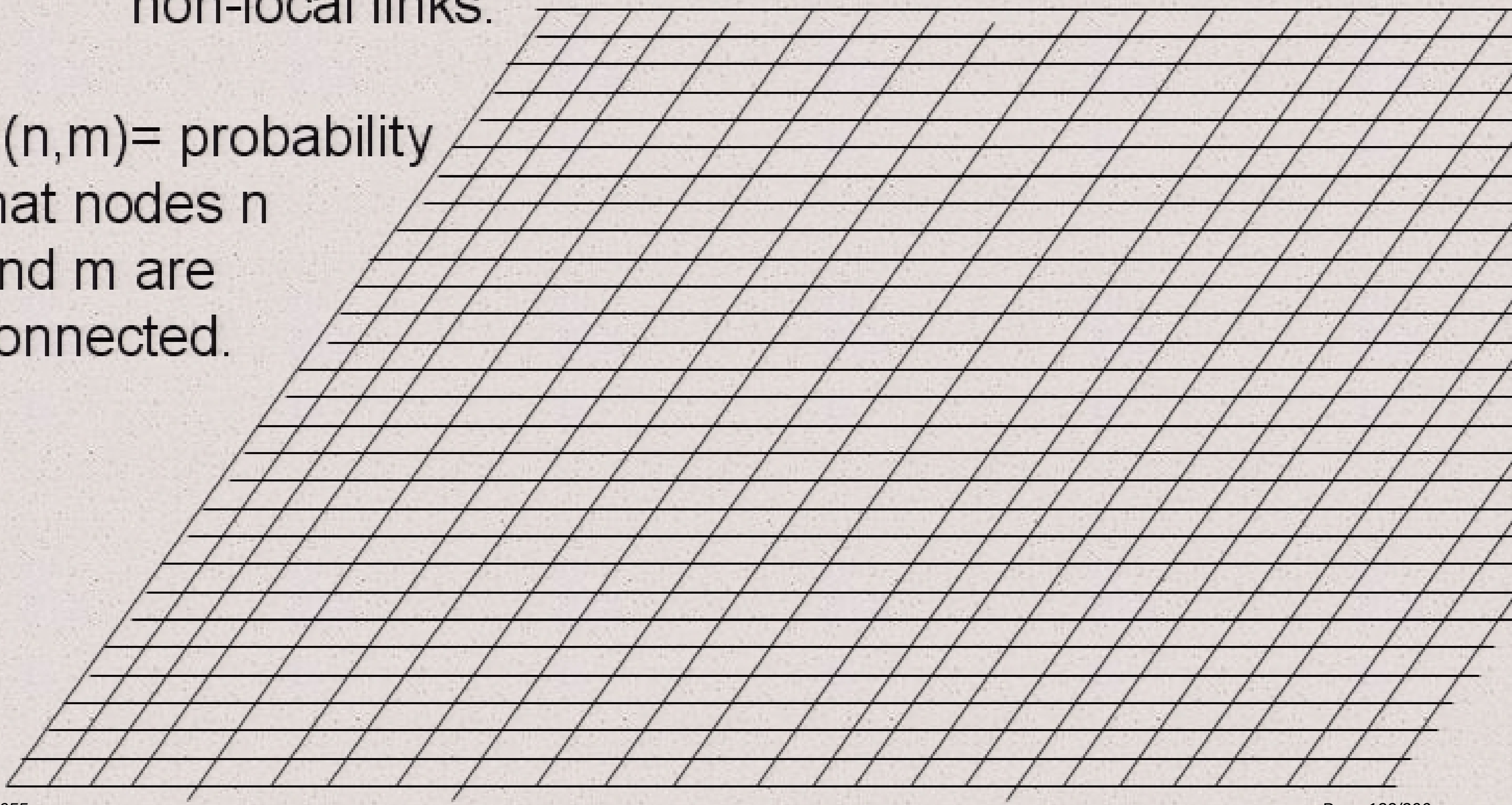
A regular lattice or weave with a random distribution of non-local links.

P(n,m)= probability that nodes n and m are connected.



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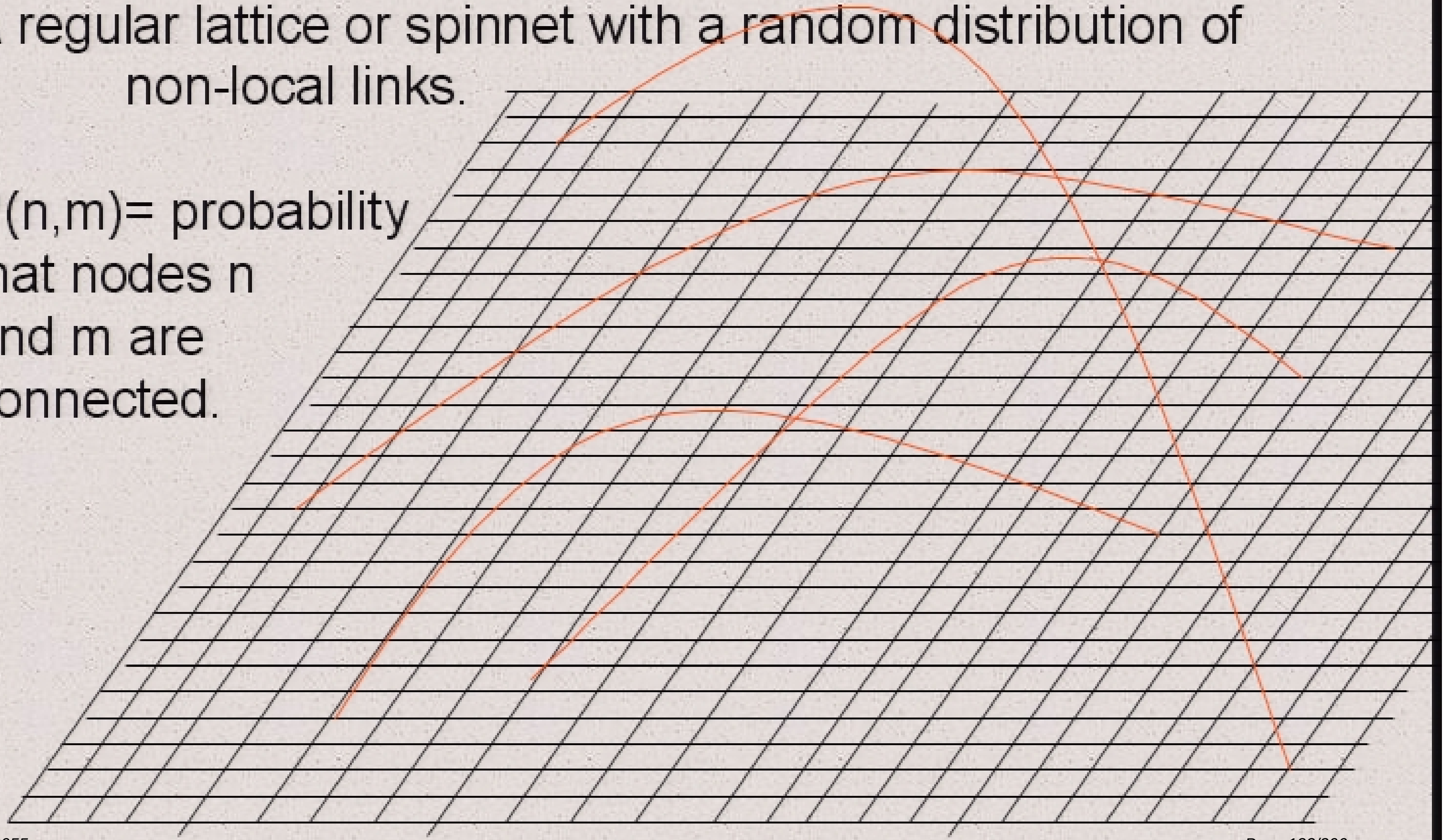

We have found so far four applications of such a conflict between micro and macro locality:

1. matter fields from gauge fields + non-locality
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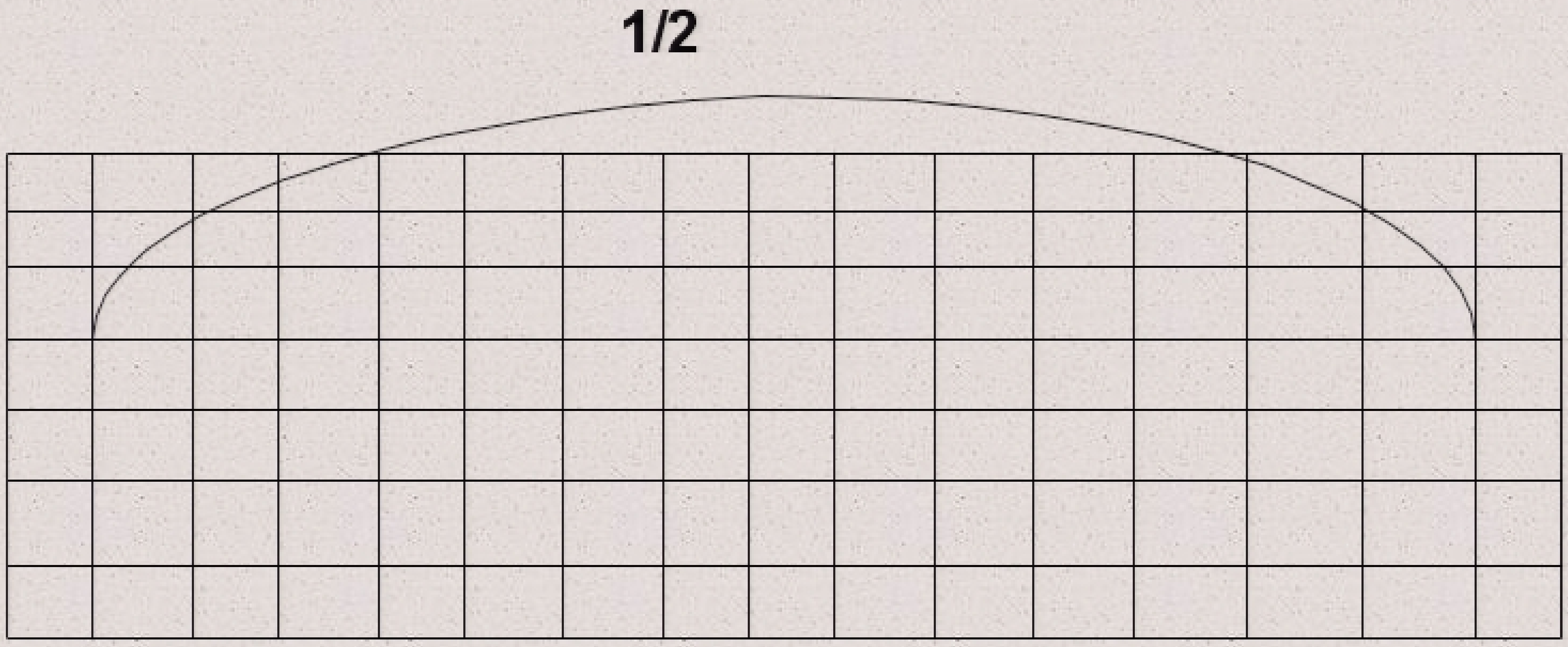
A spin network with a non-local link



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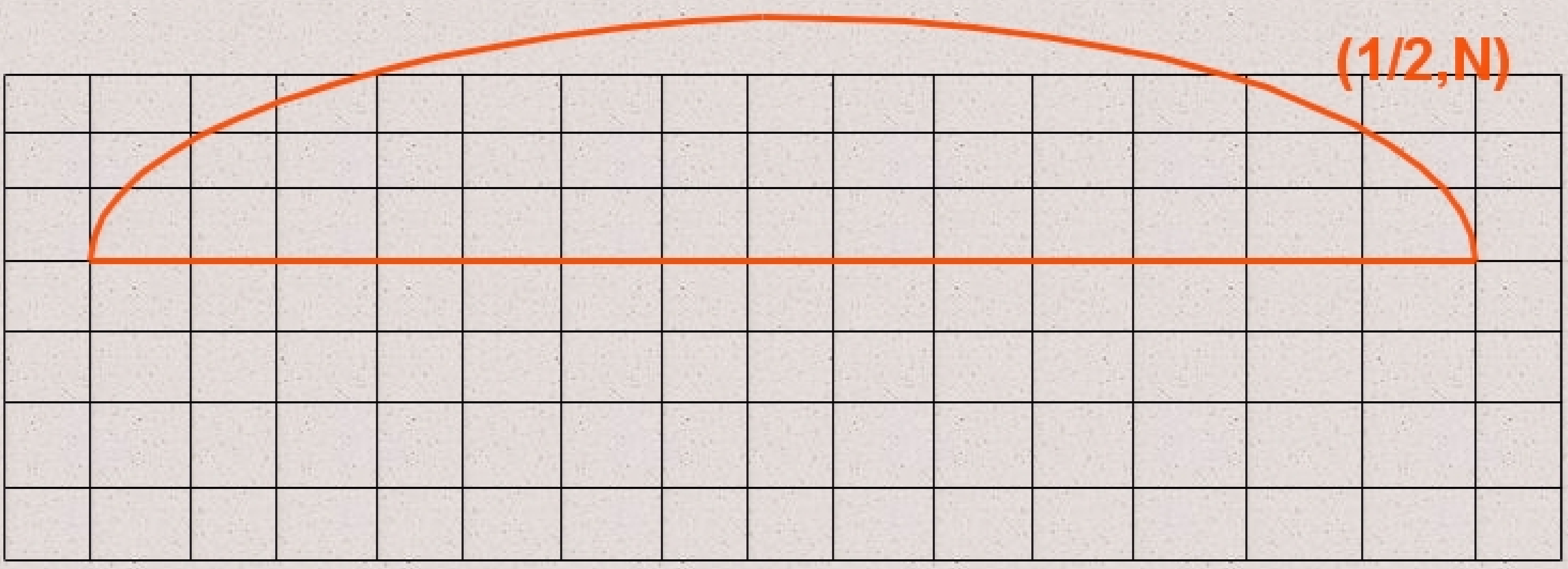

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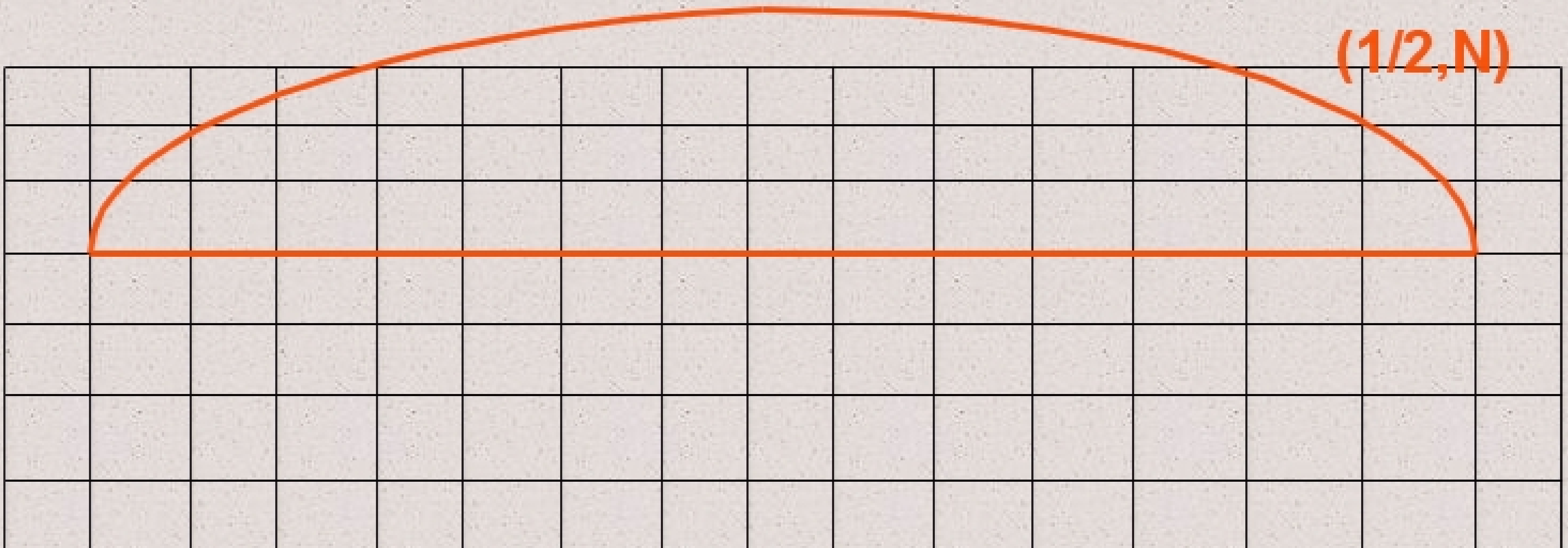

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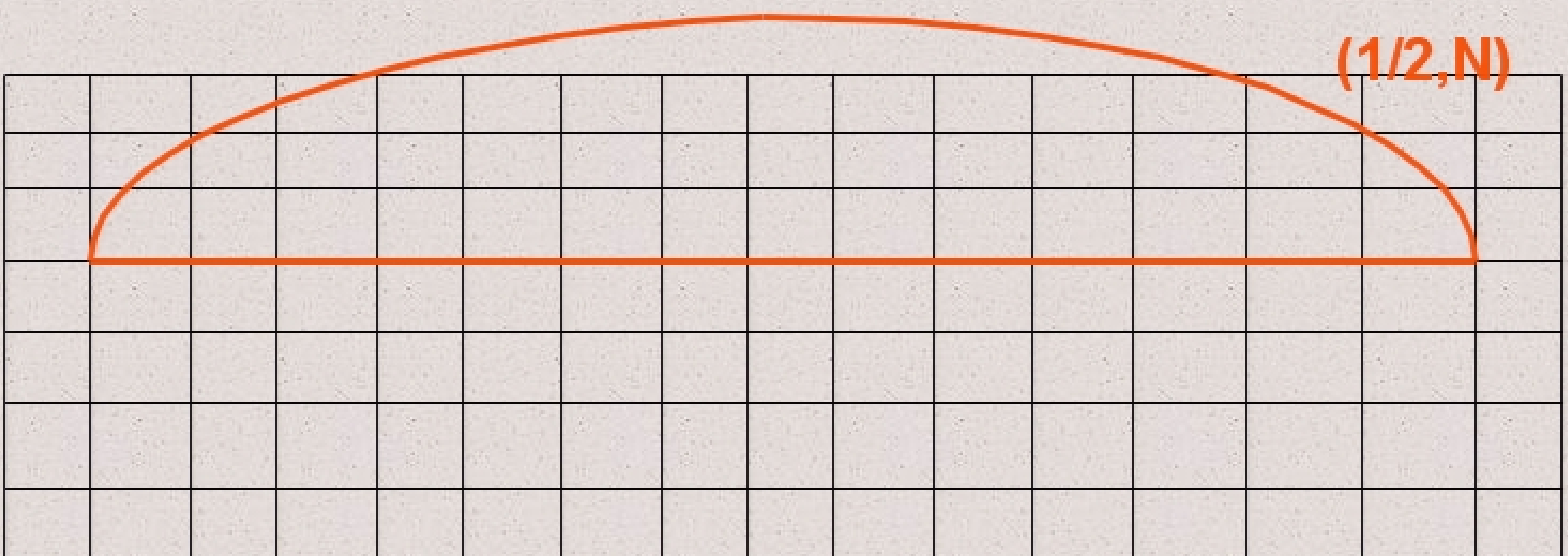

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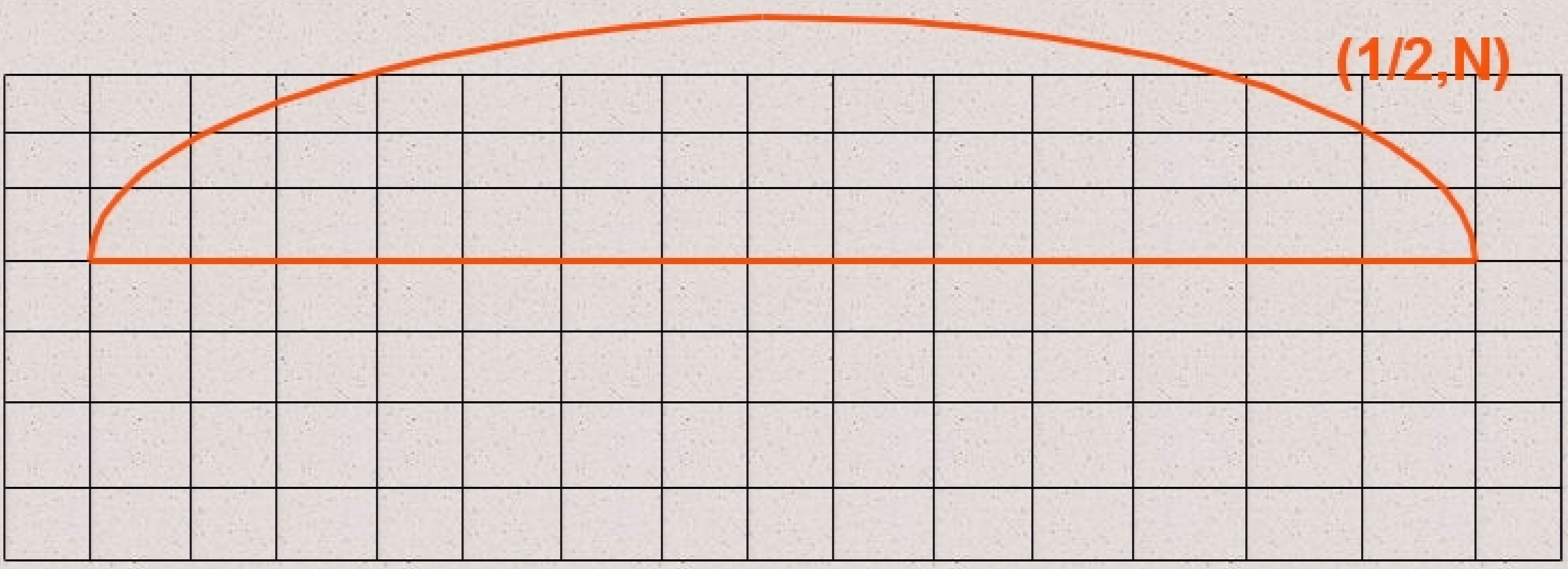

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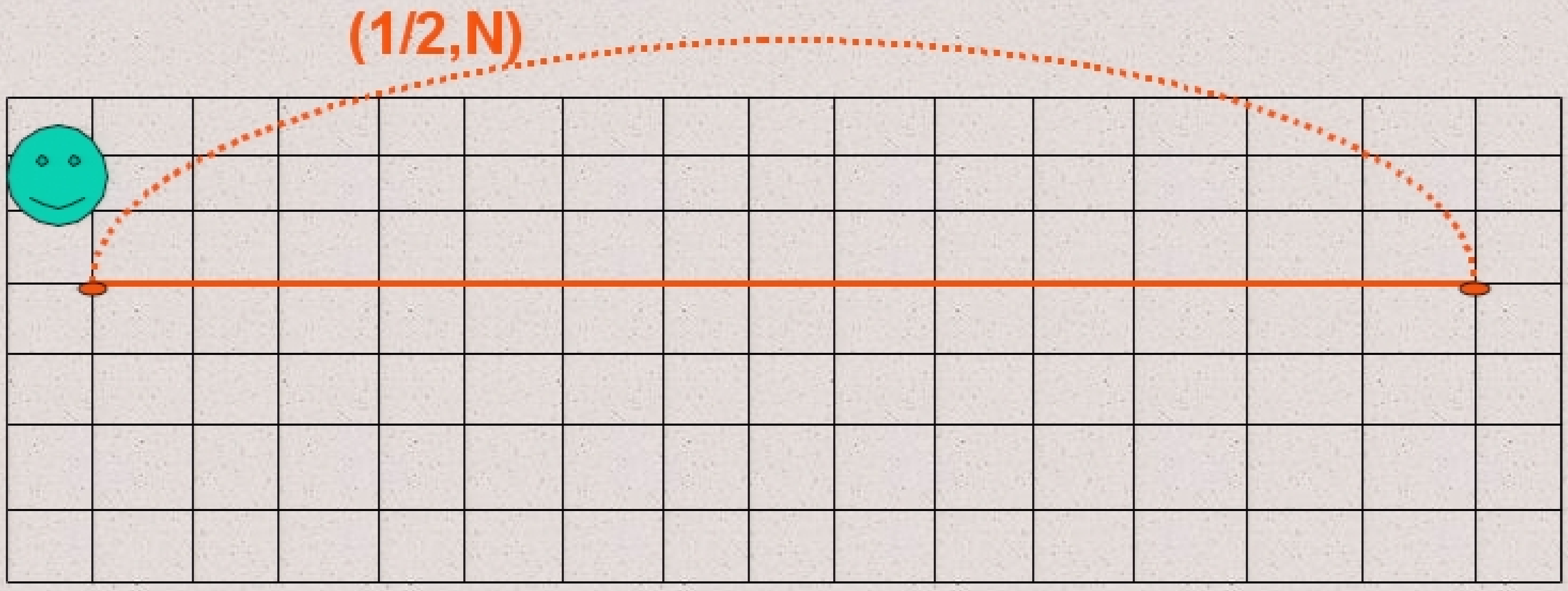

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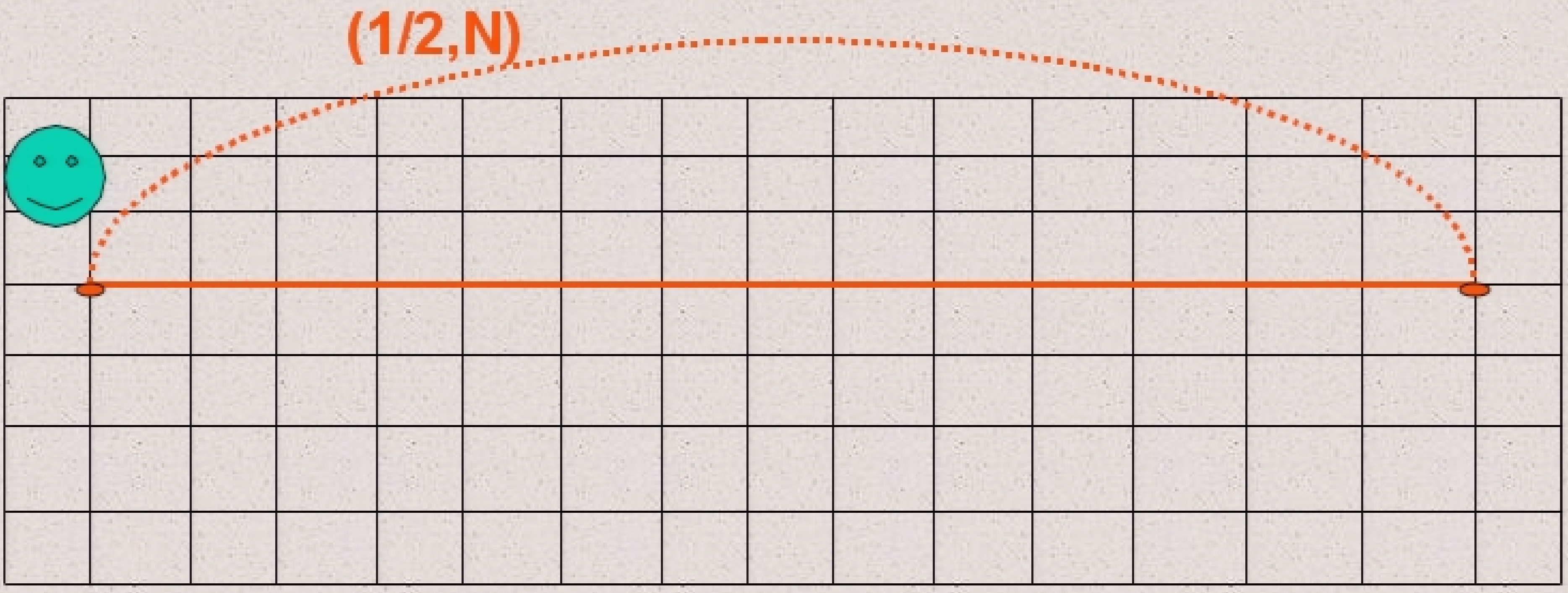

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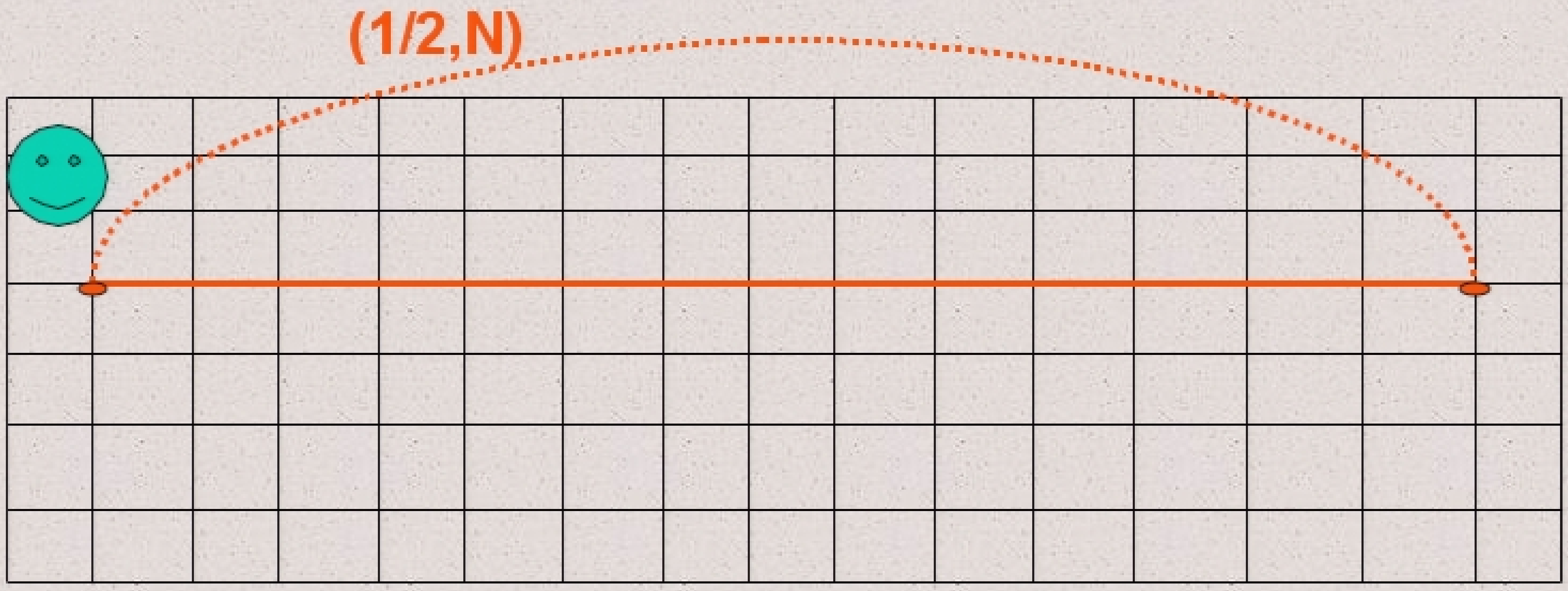

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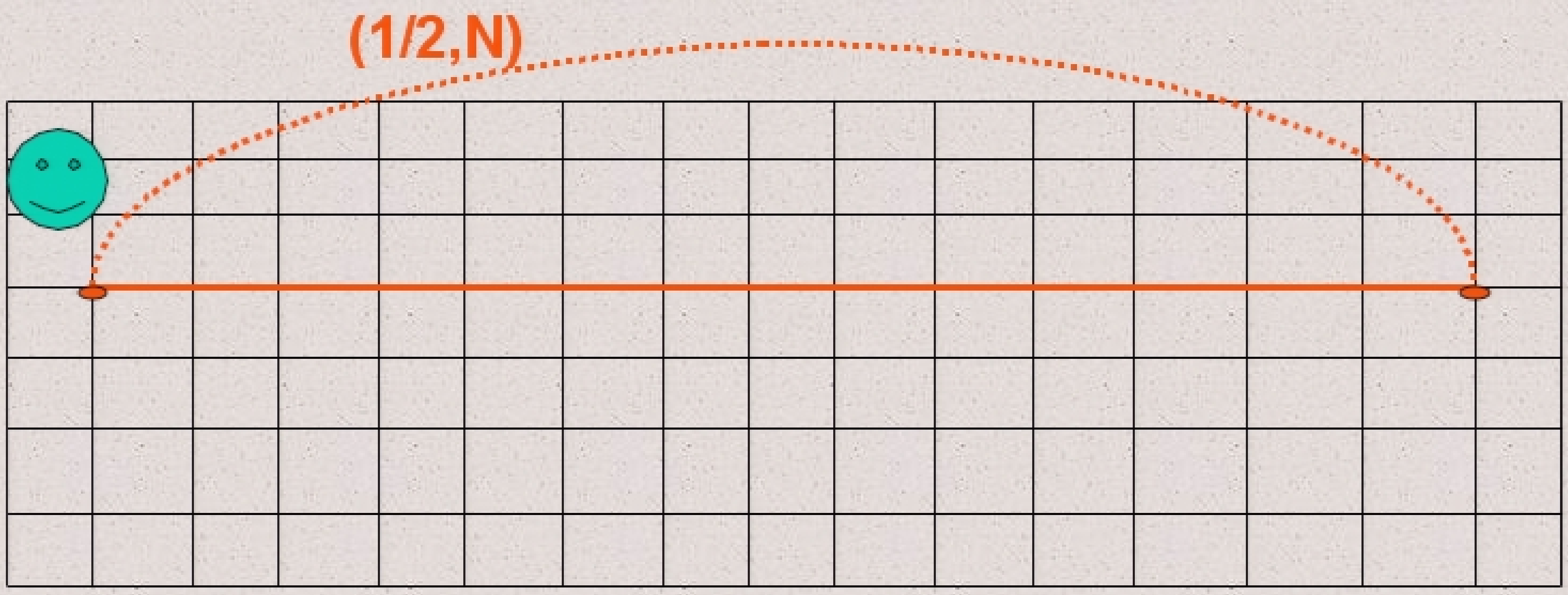

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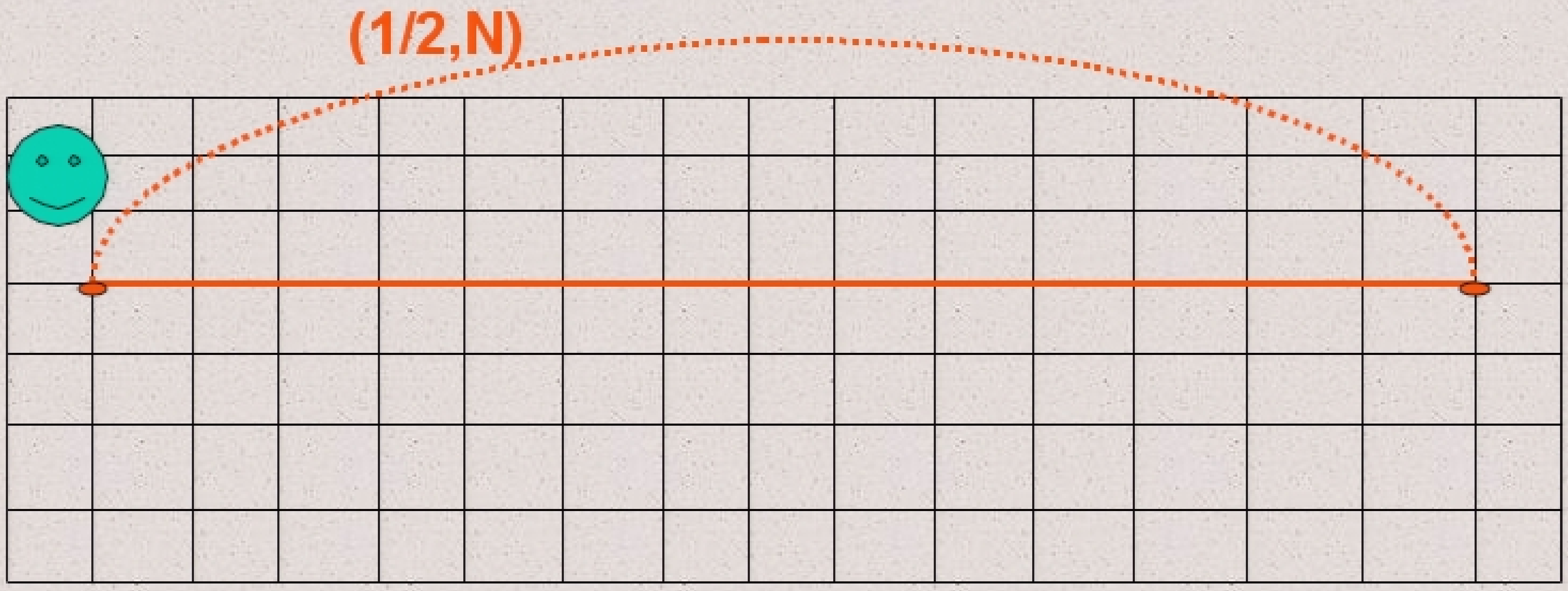

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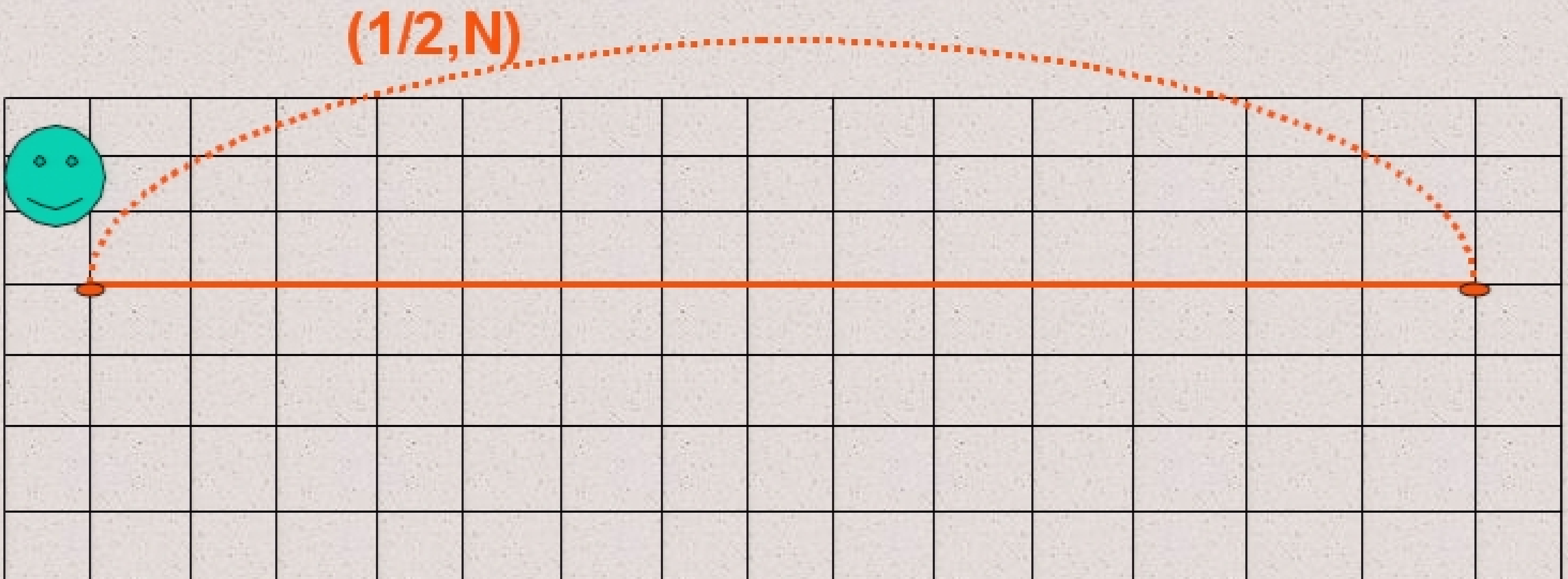

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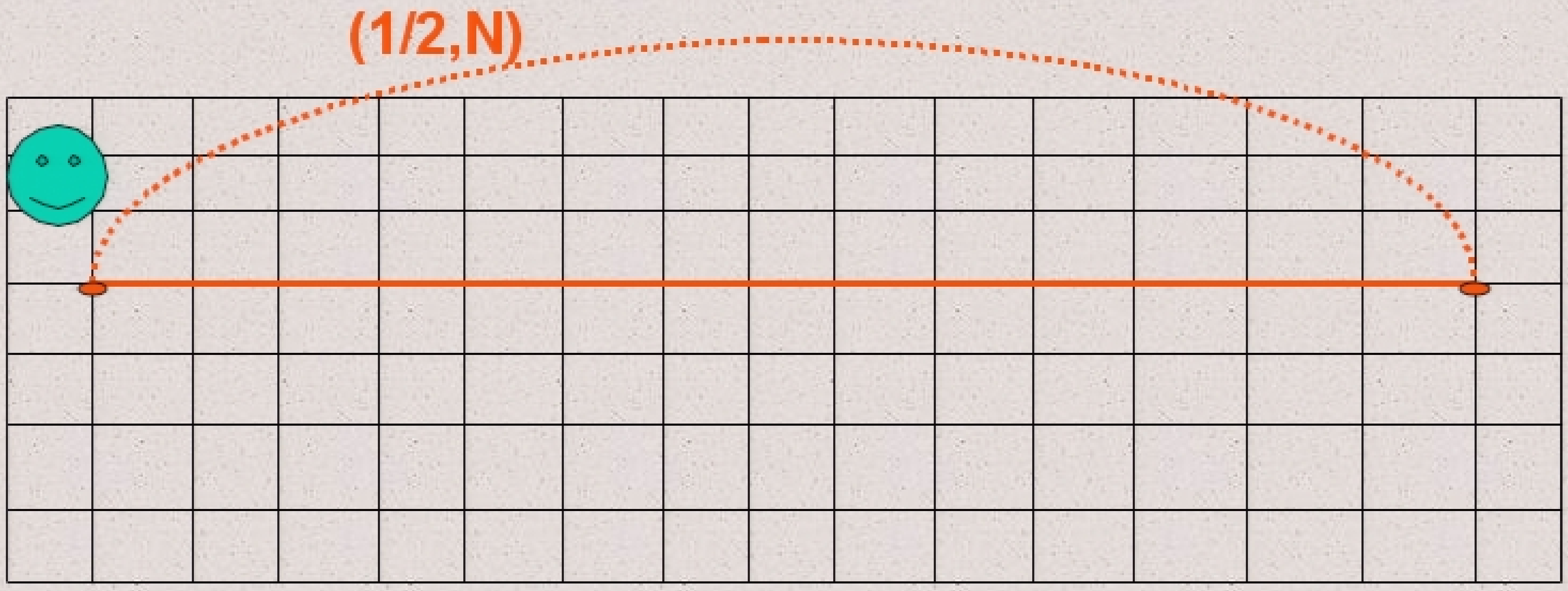

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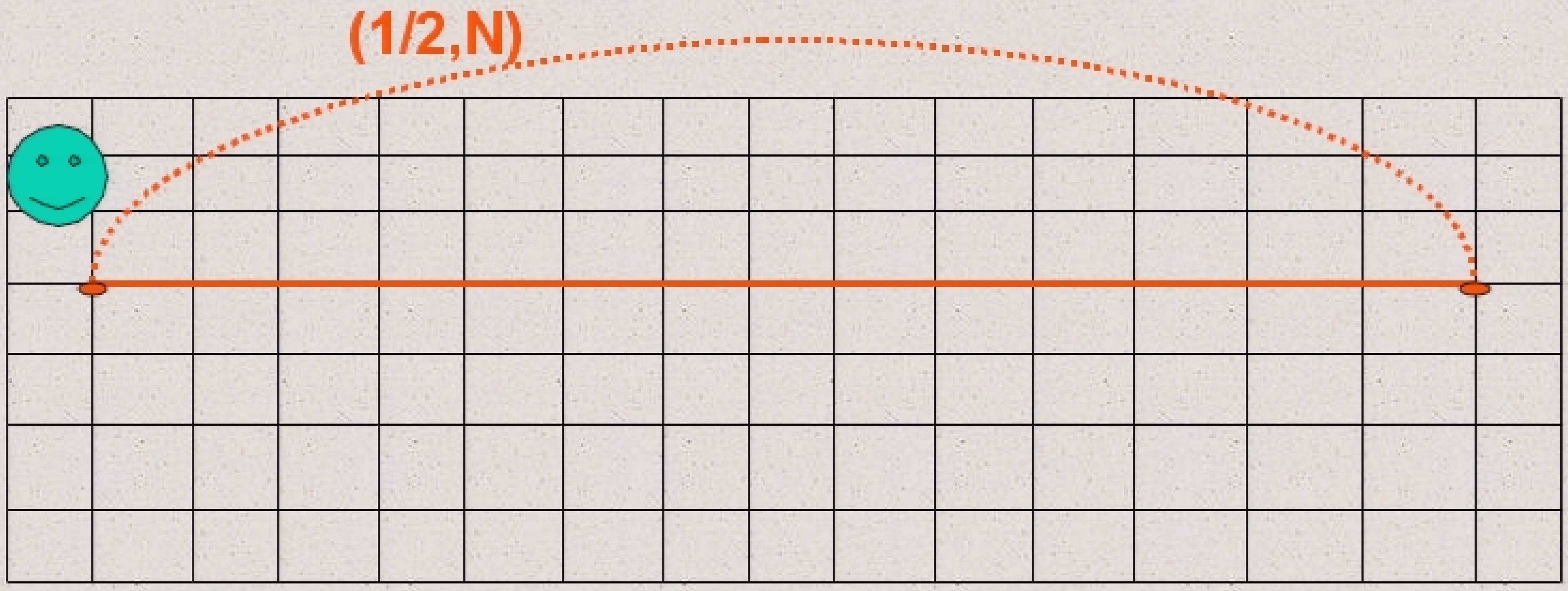

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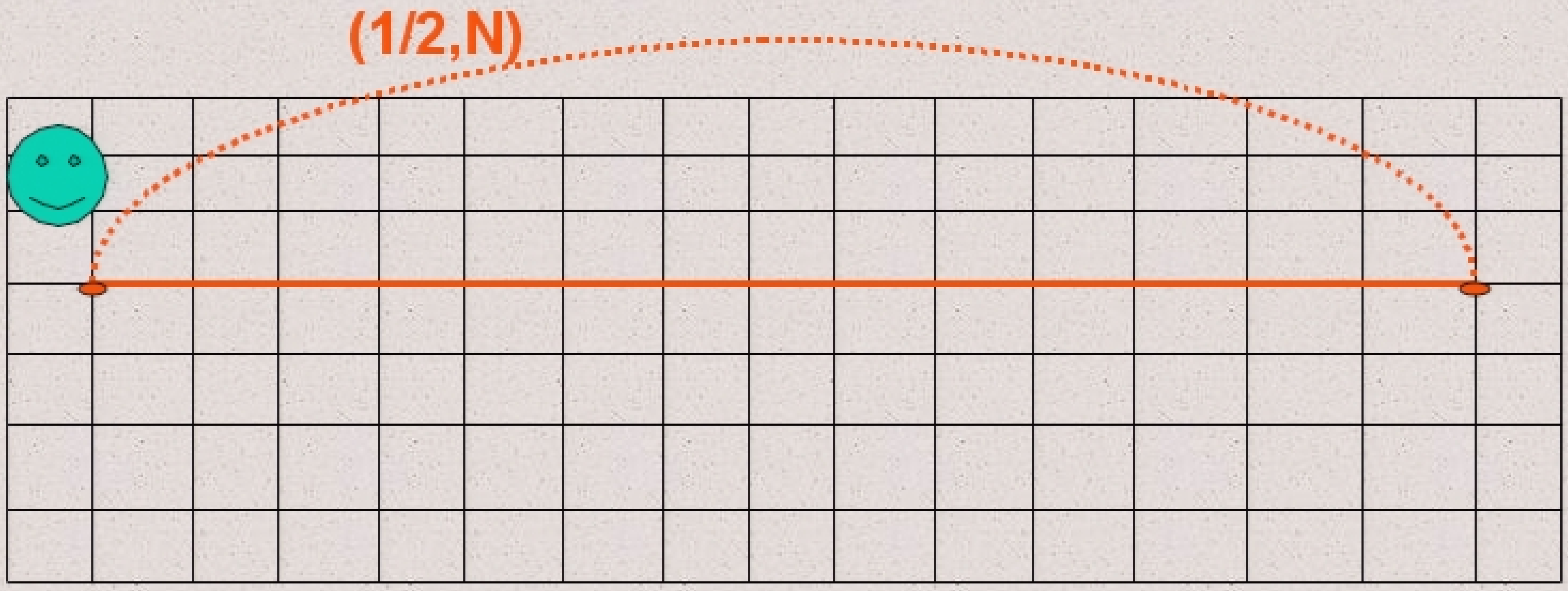

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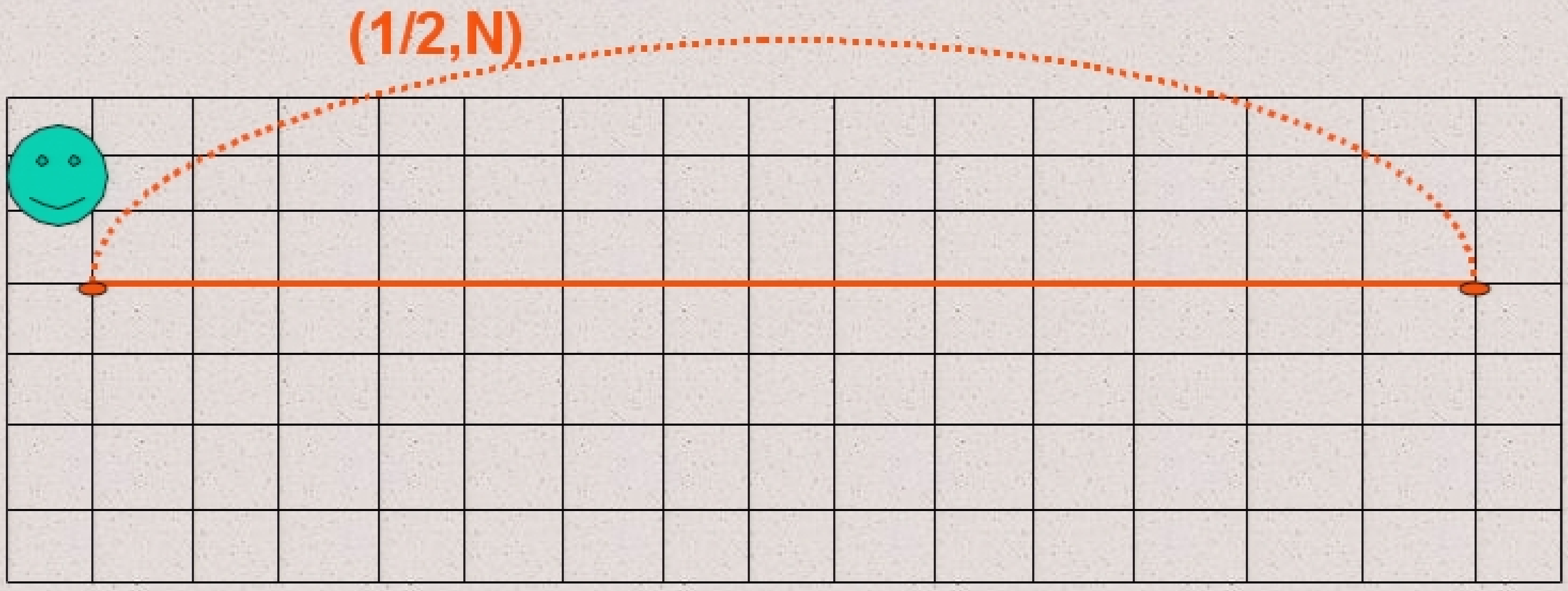

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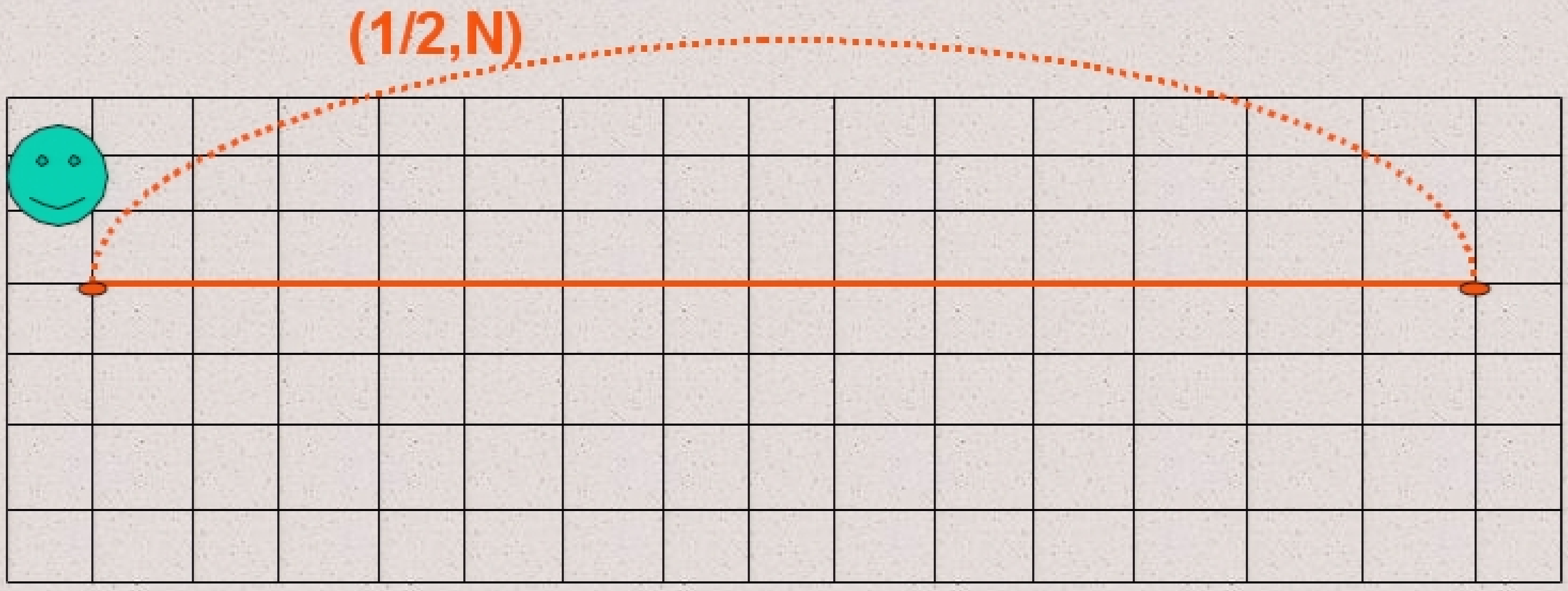

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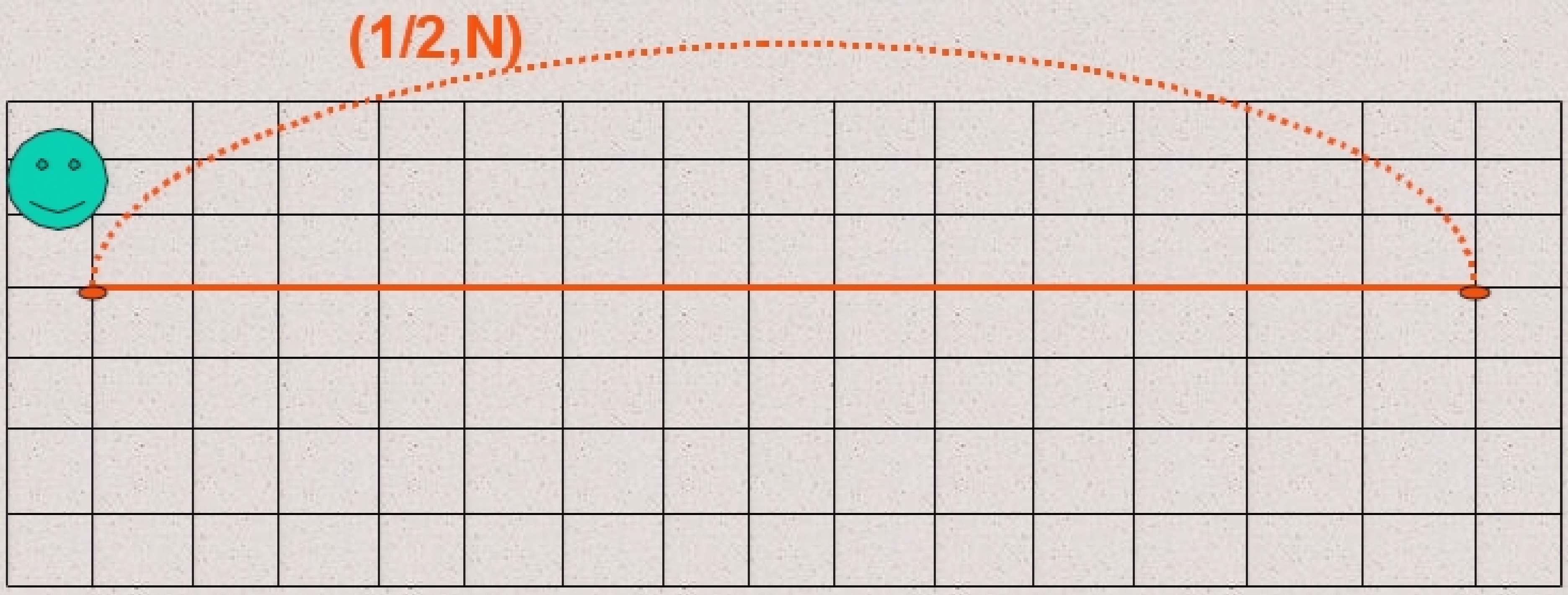

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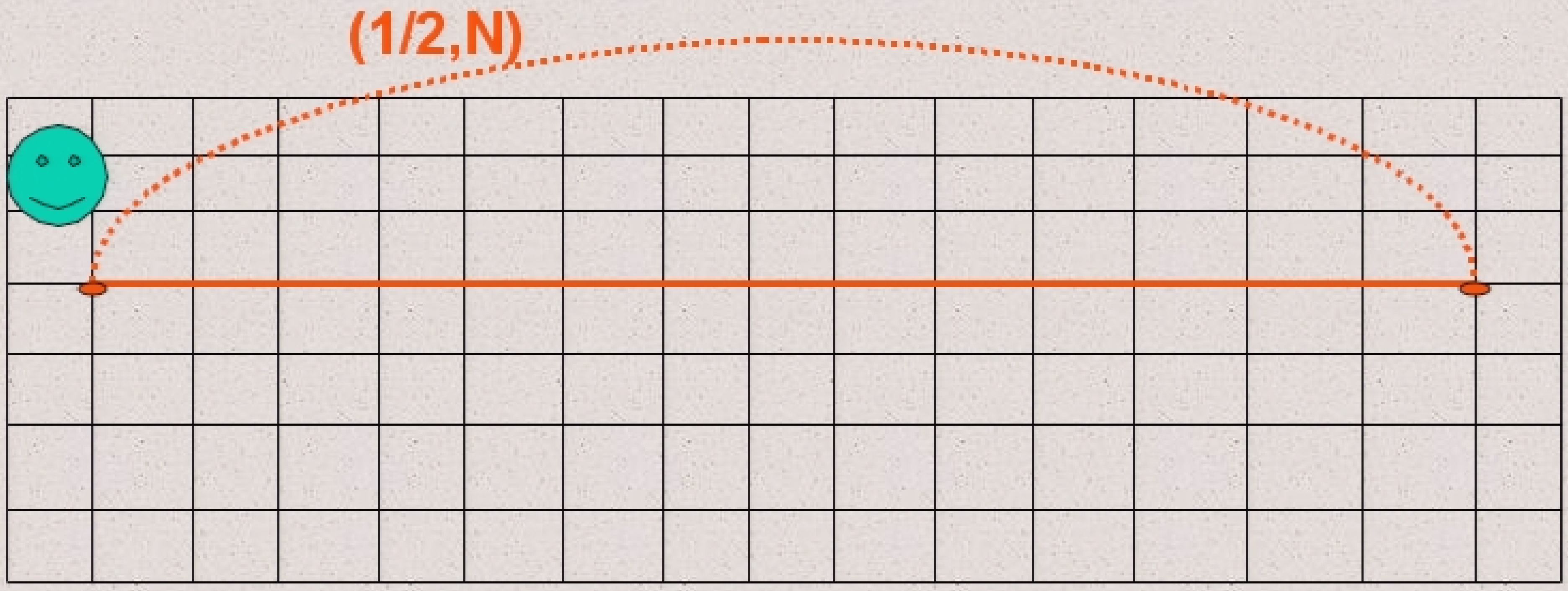

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Could this work?

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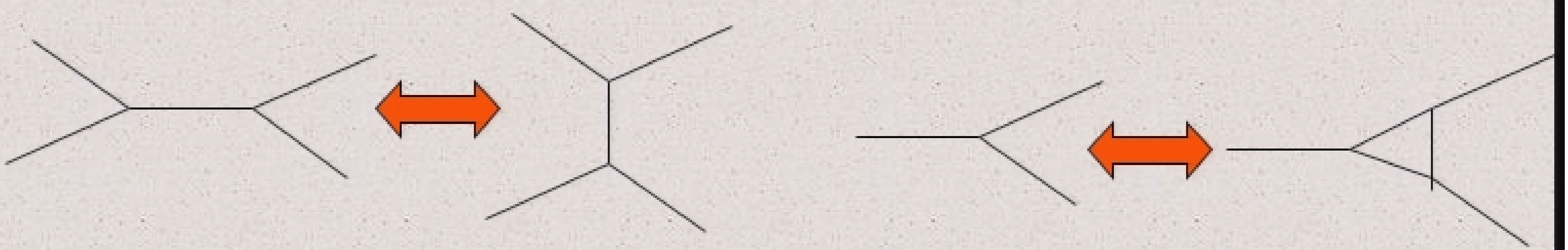

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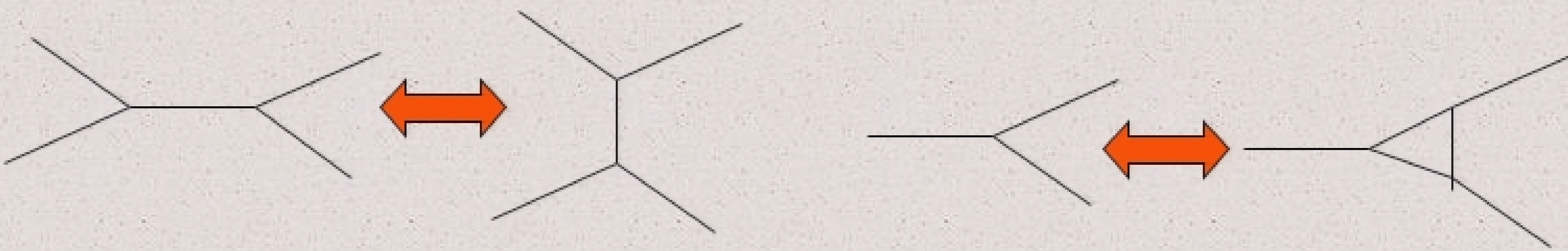

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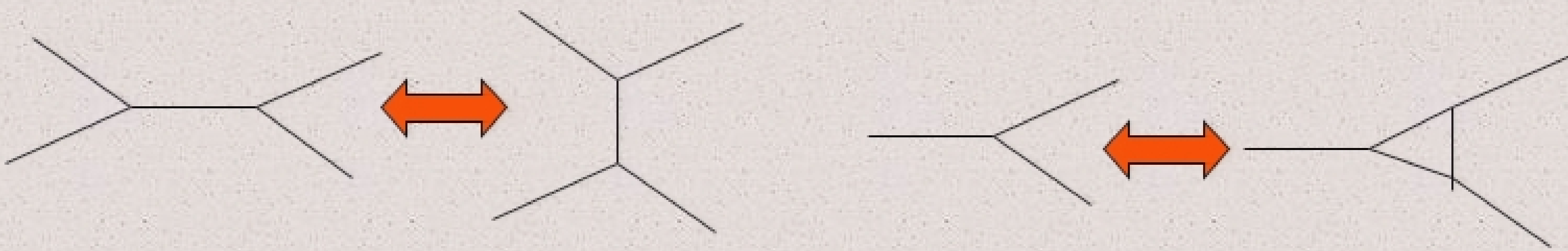

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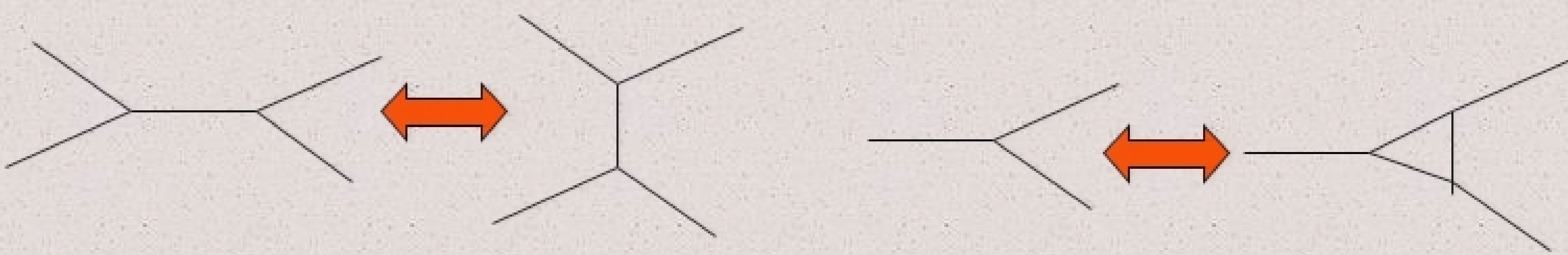

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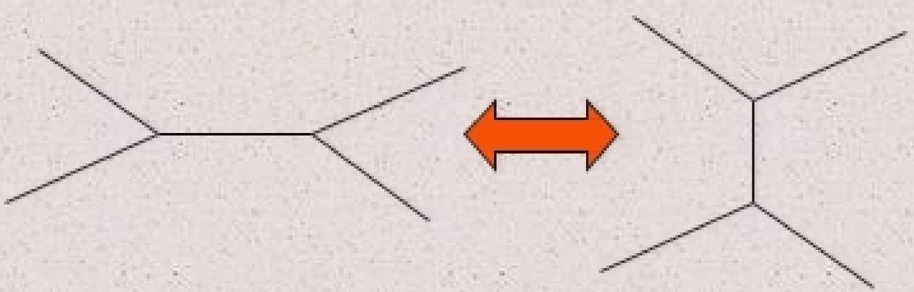

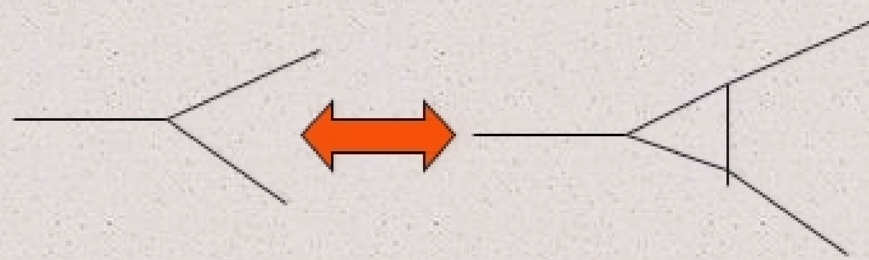

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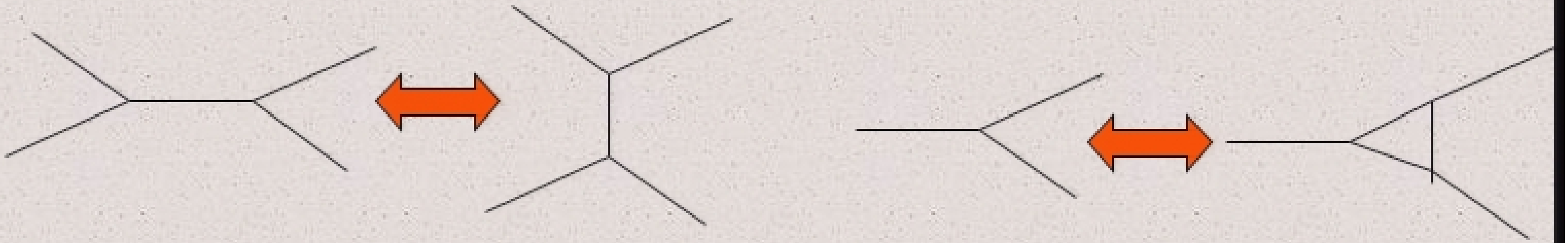

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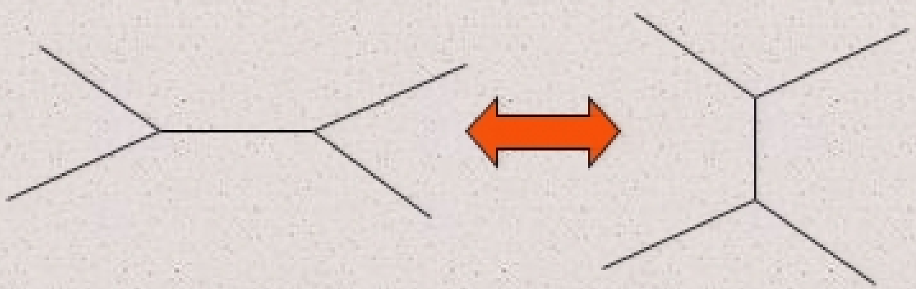

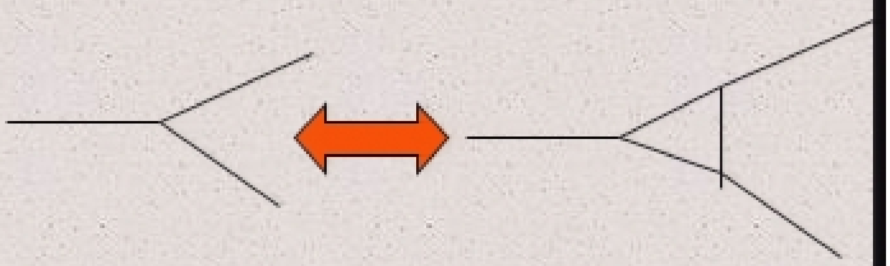

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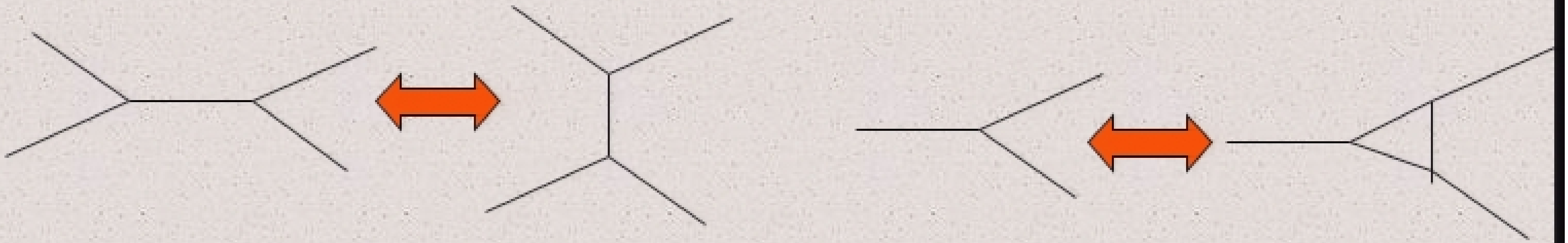

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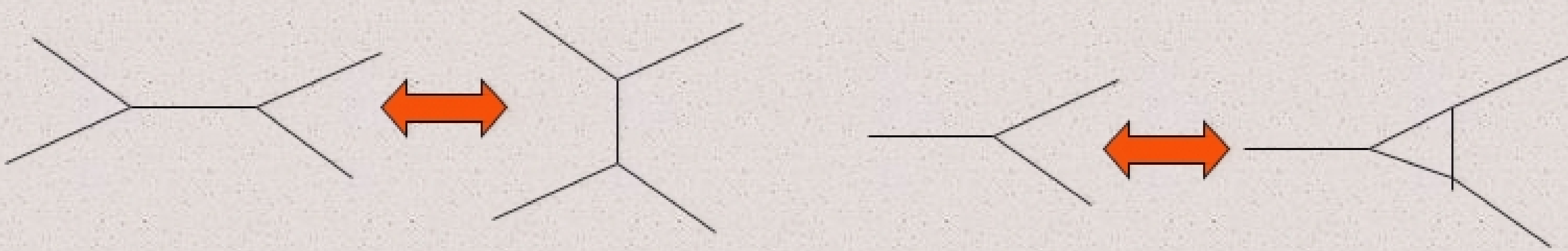

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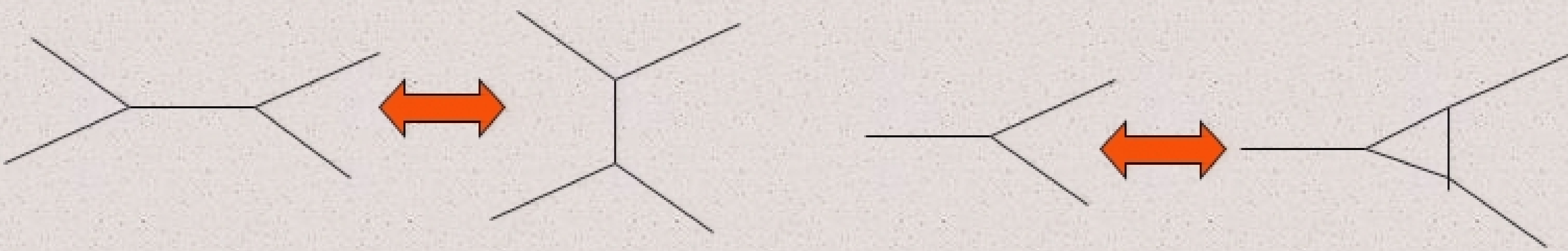

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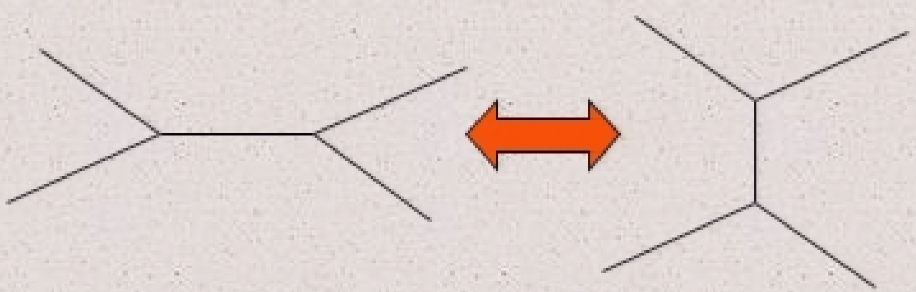

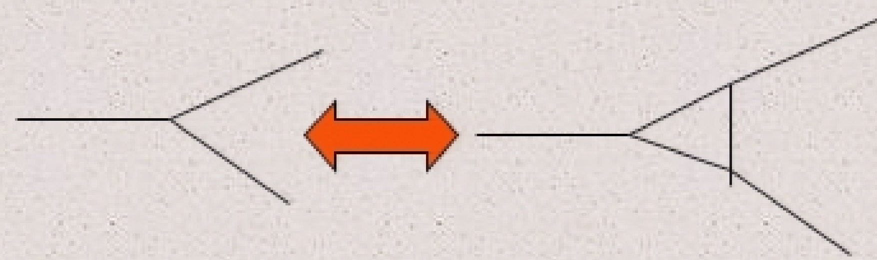

fm gr-qc/9704013

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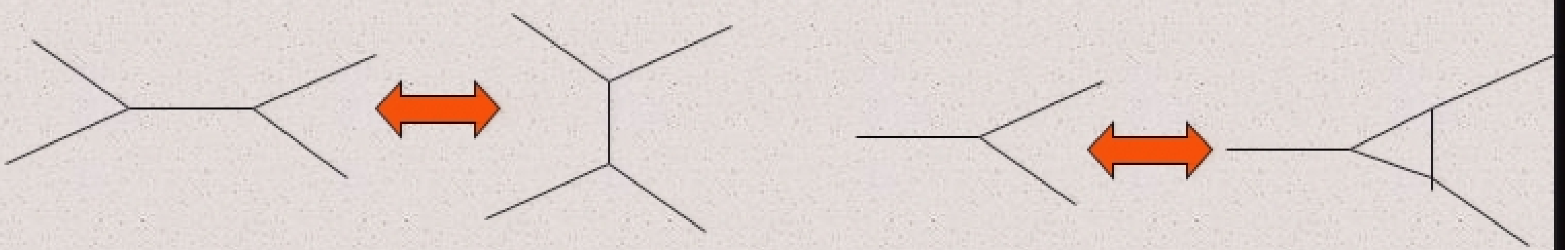

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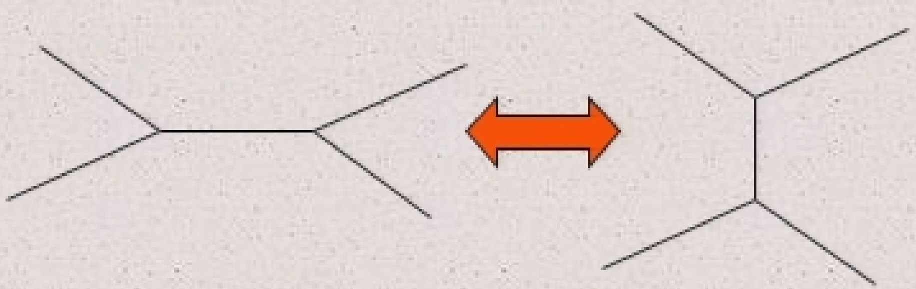

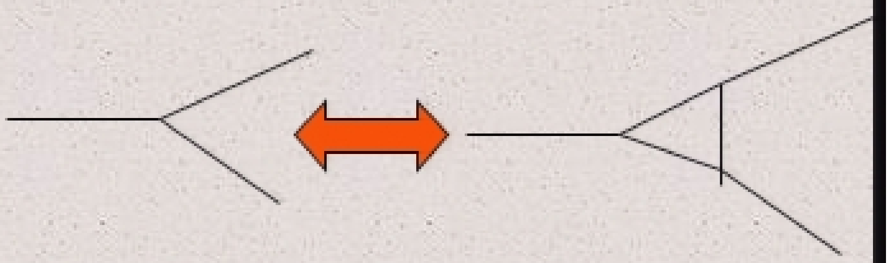

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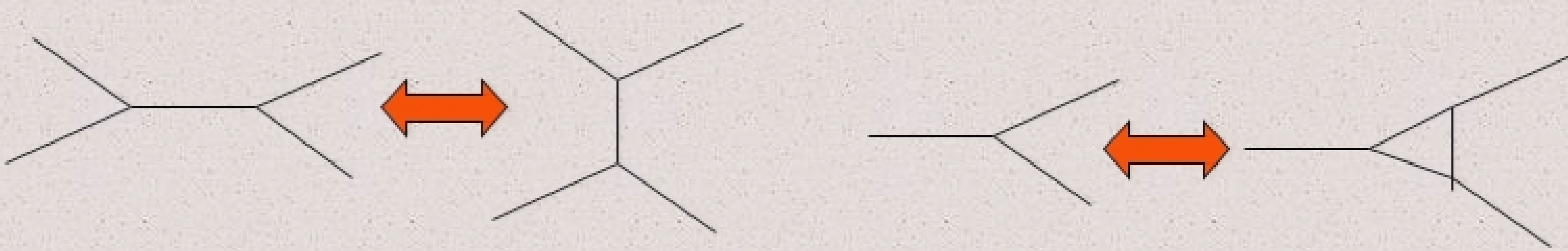

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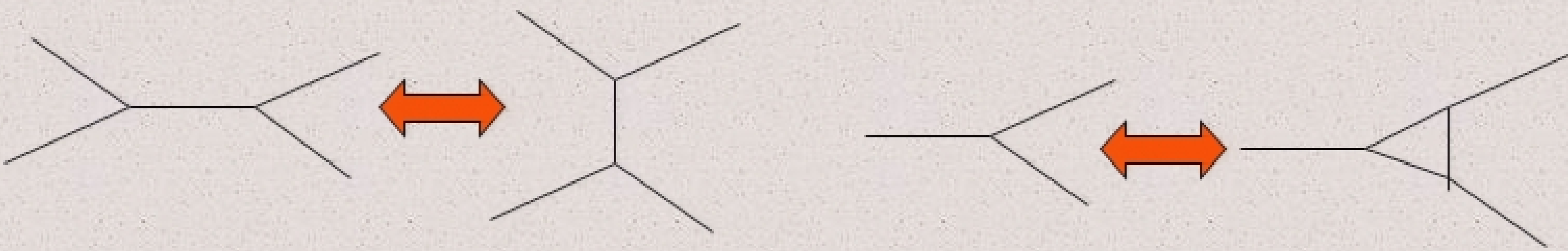

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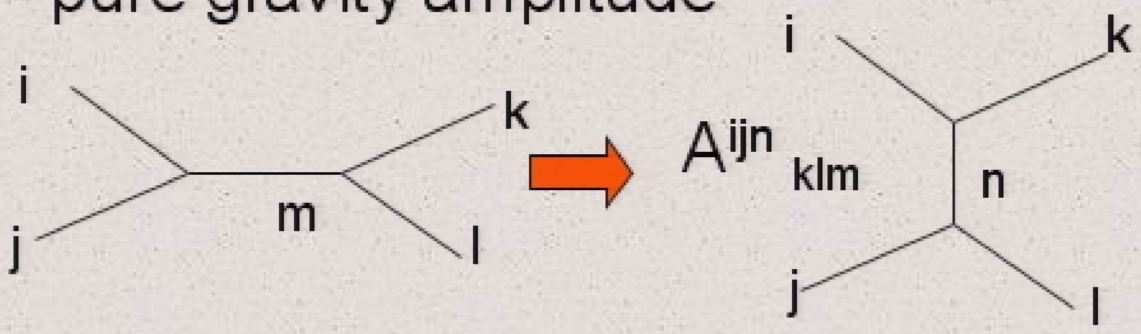
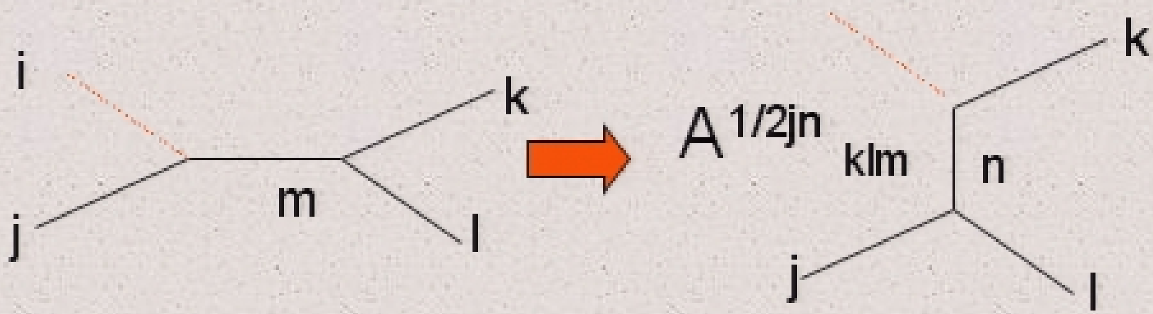
Relation between fermion and gravity dynamics:

pure gravity amplitude



Let the i=1/2 line be non-local



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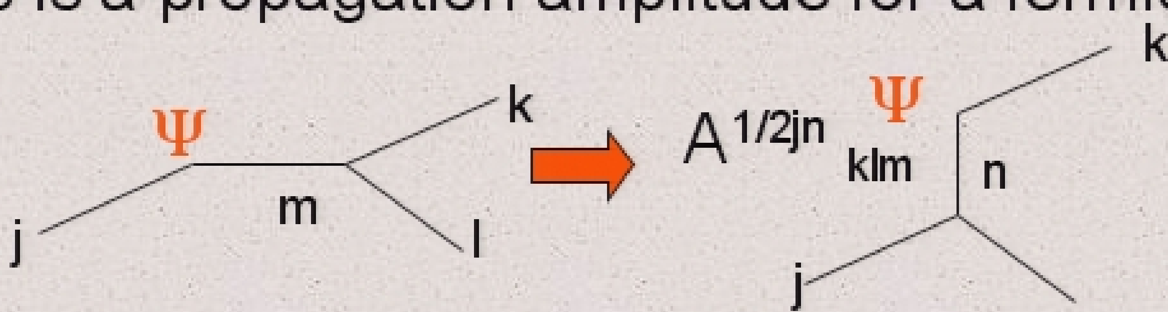

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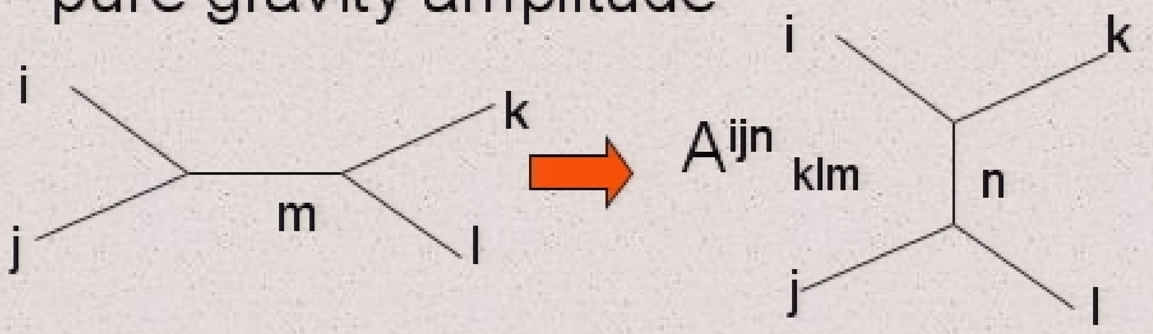

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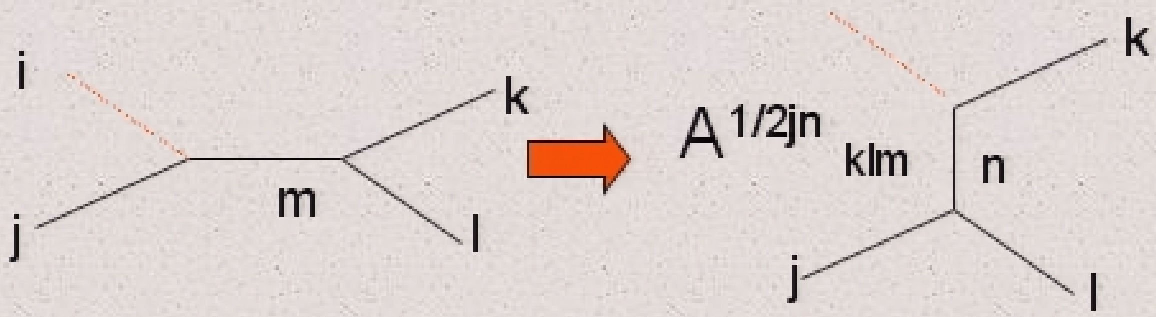

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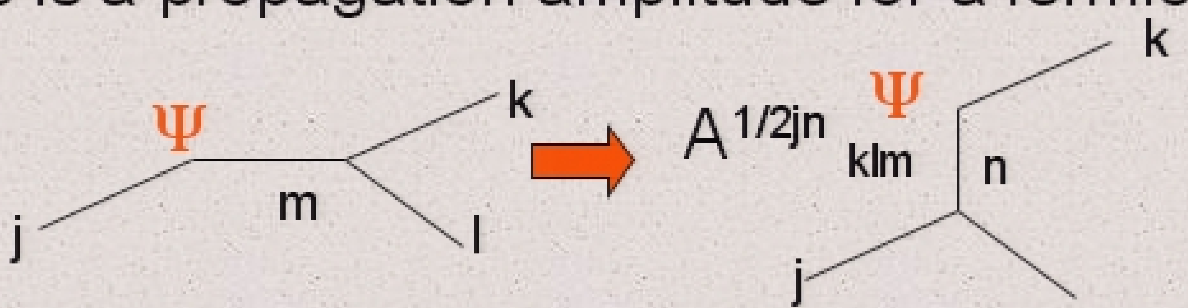

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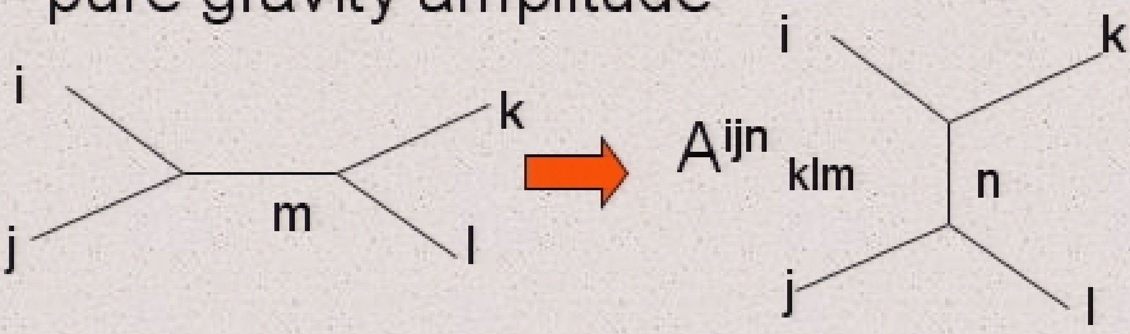

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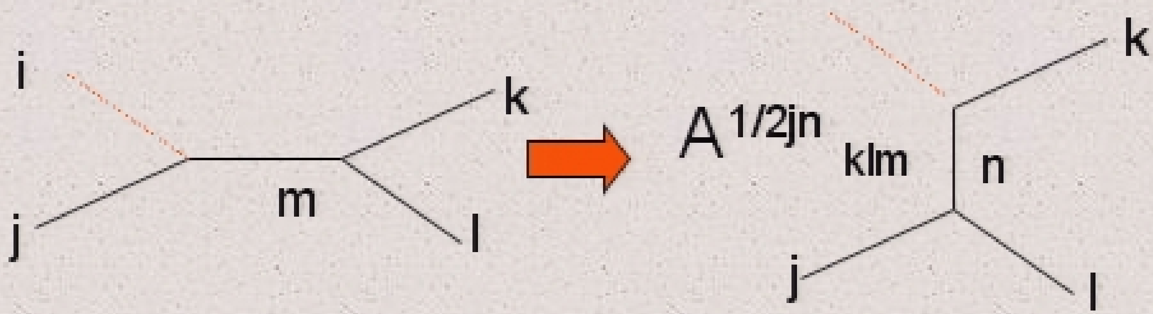

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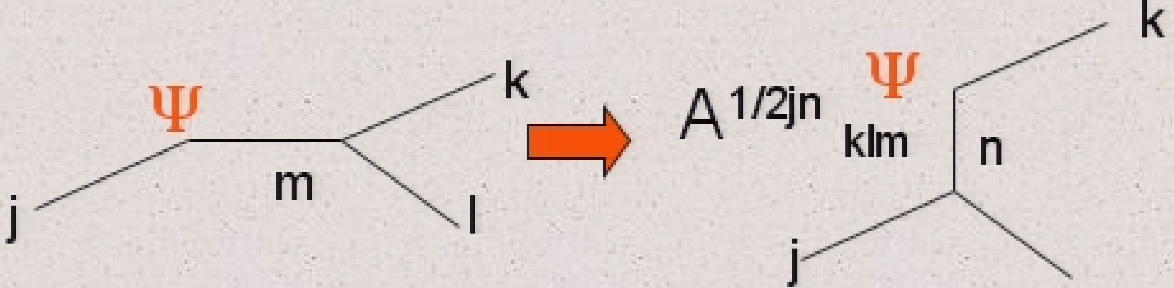

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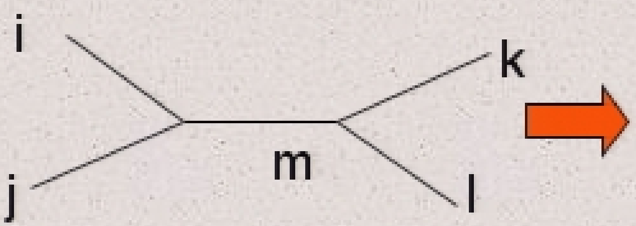
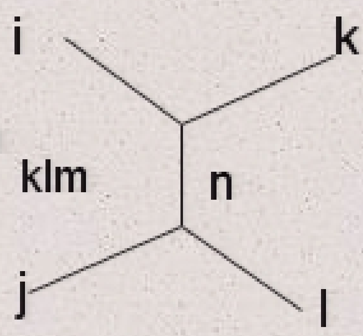


$A^{ijn}{}_{klm}$



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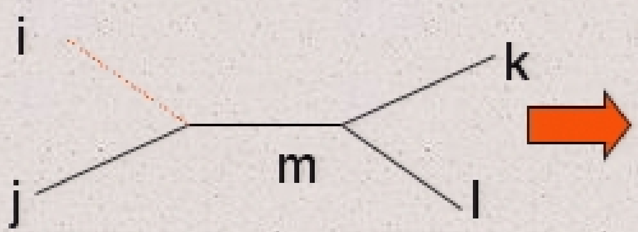

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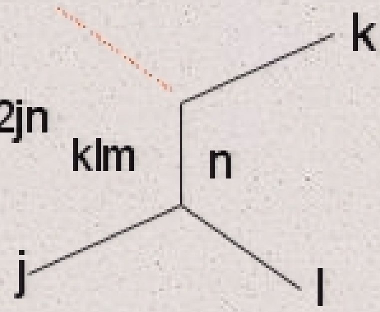

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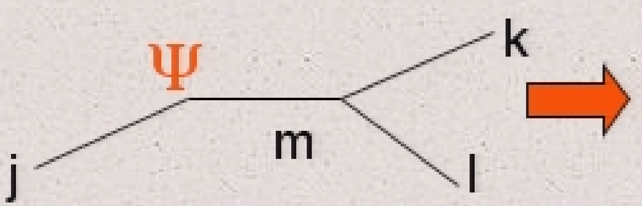

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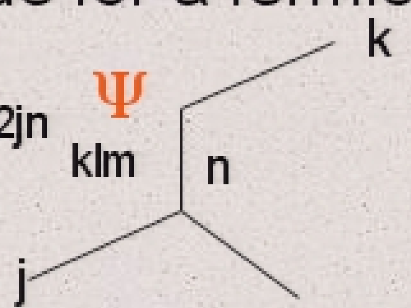

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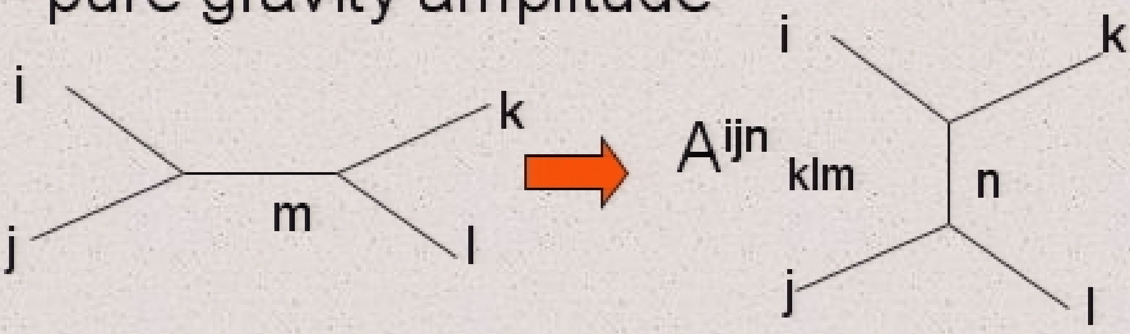
pure gravity amplitude



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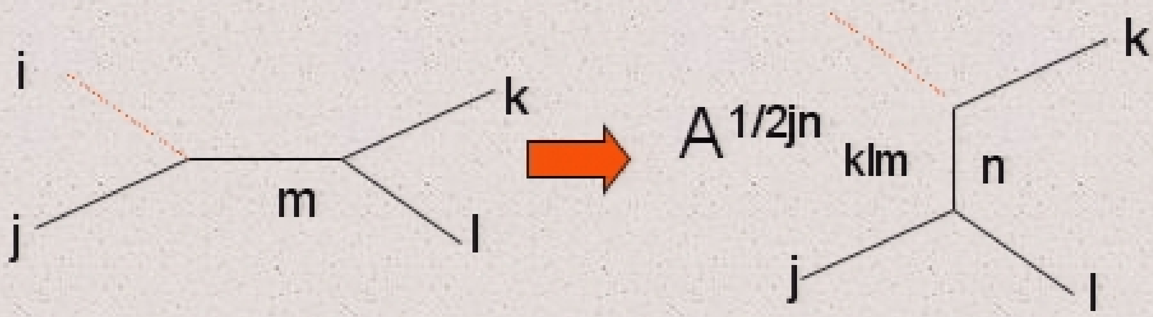

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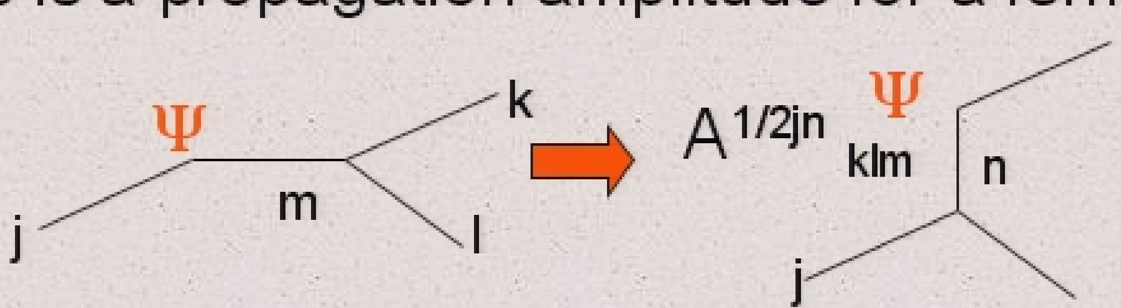

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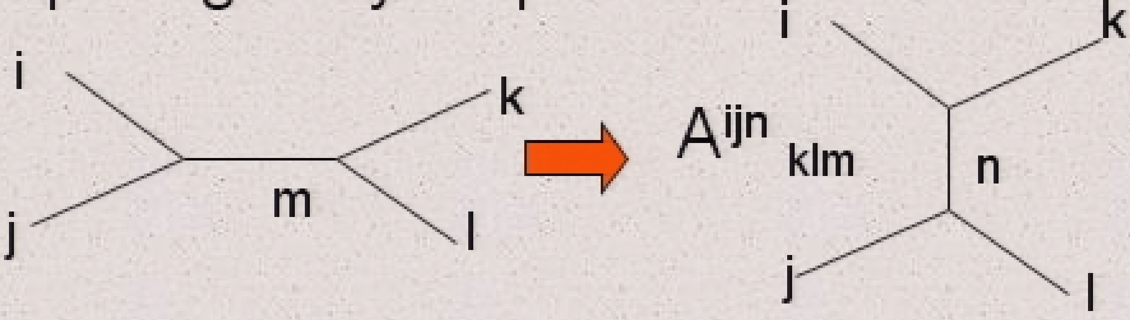

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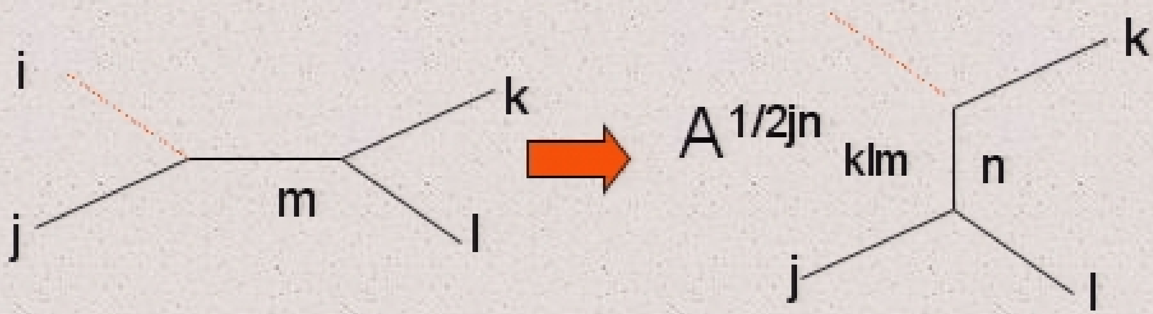

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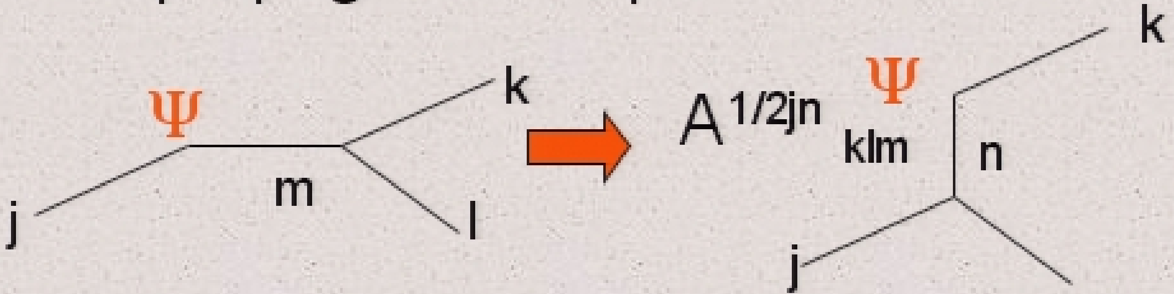

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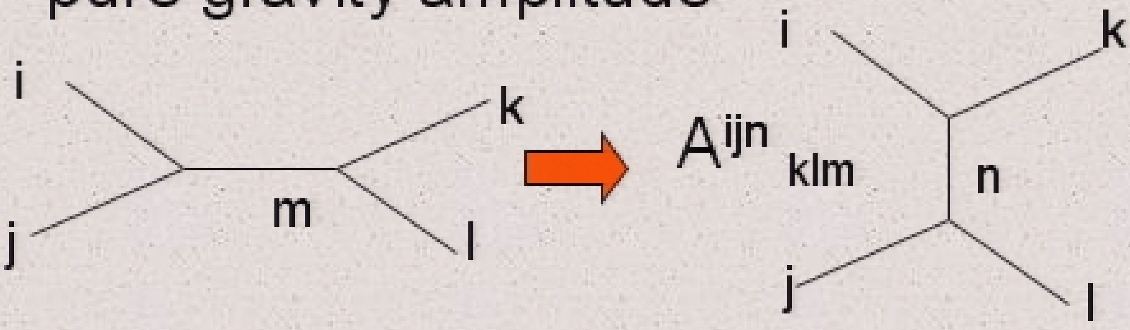

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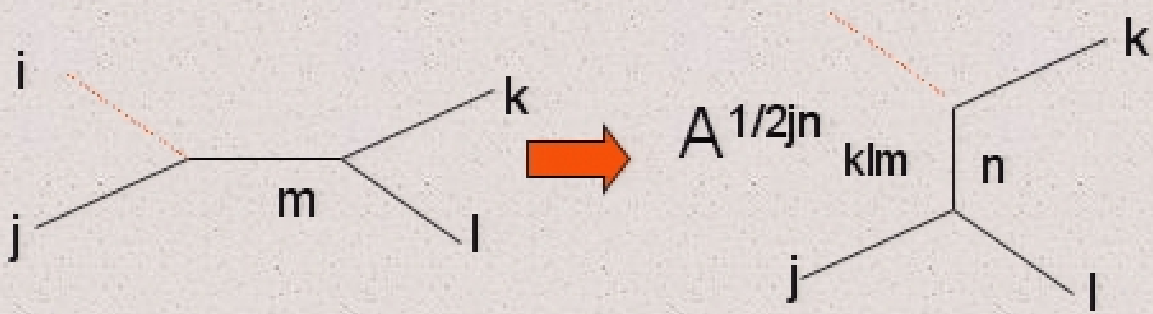

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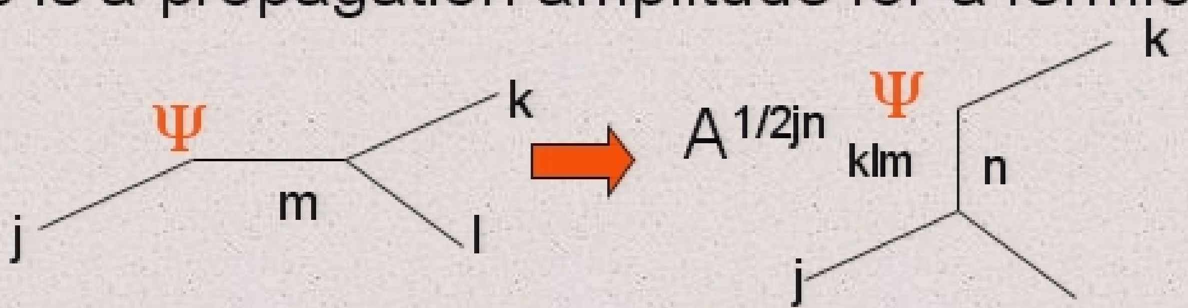

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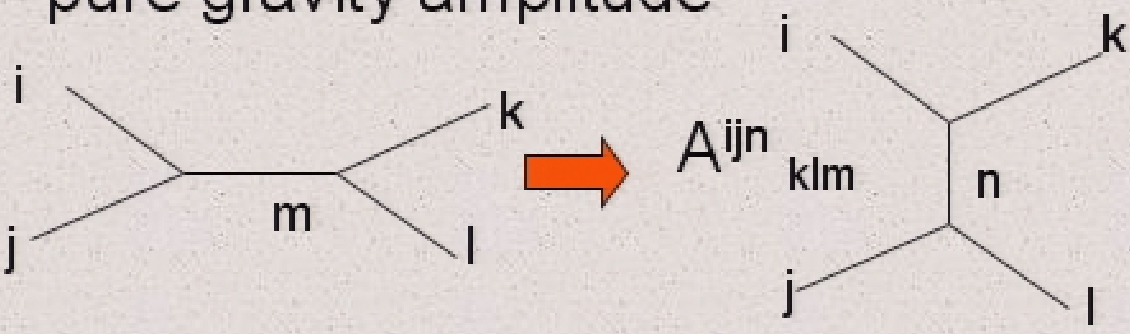

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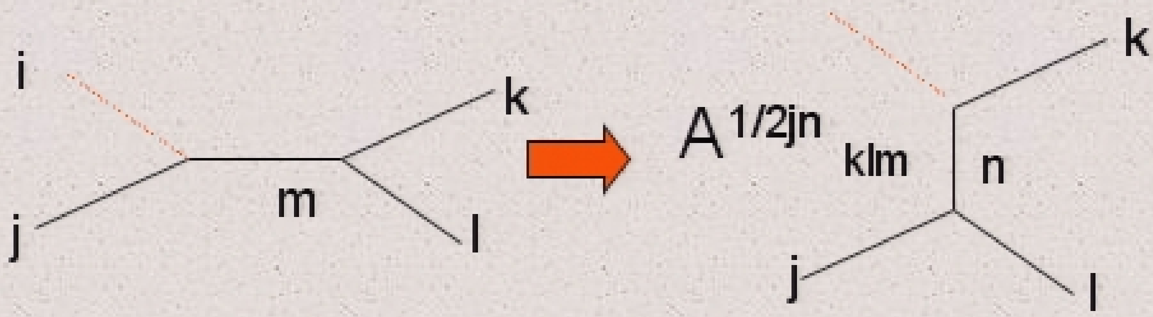

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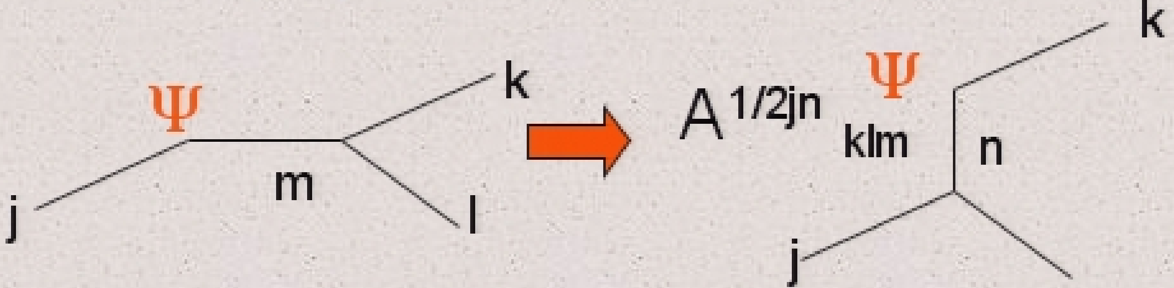

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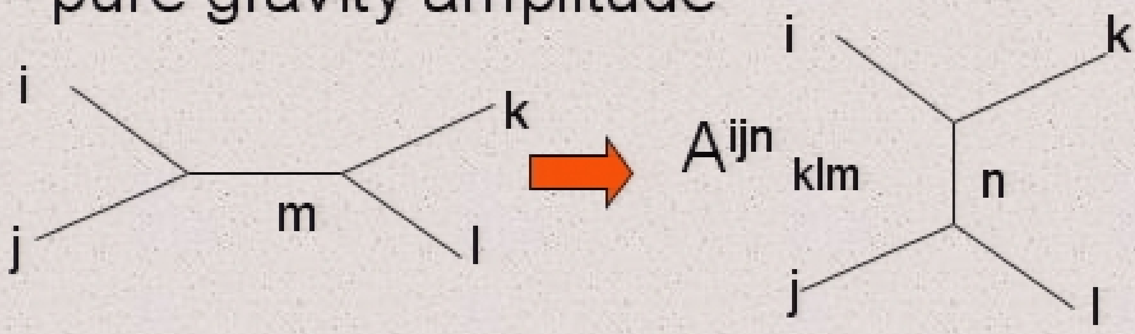

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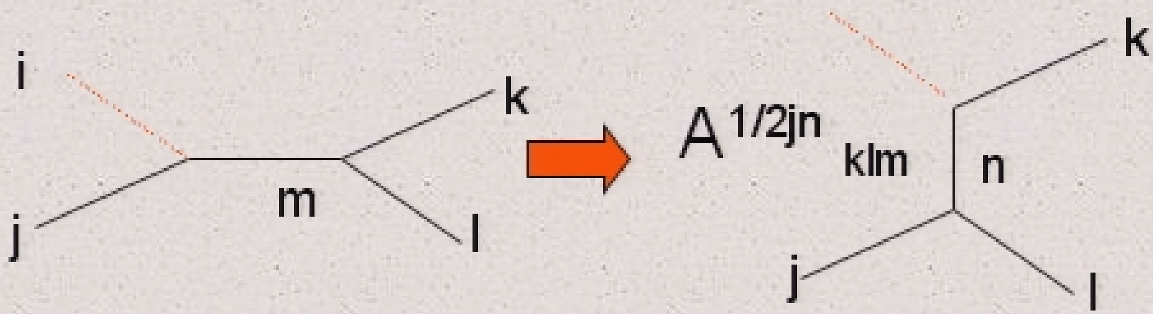

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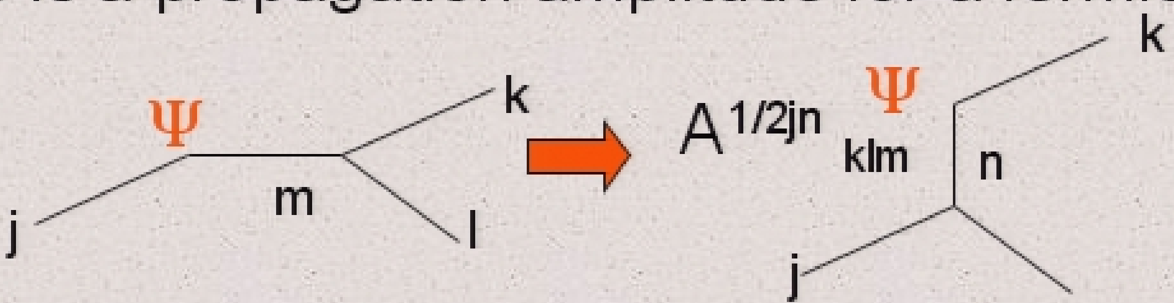

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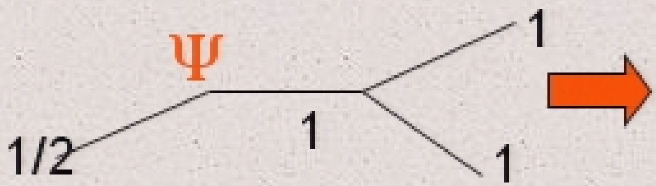
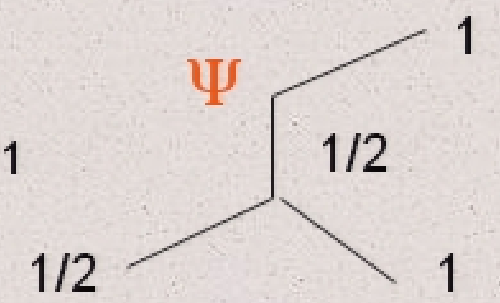
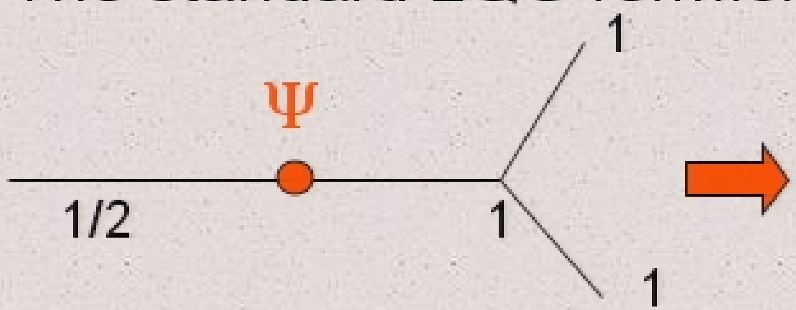


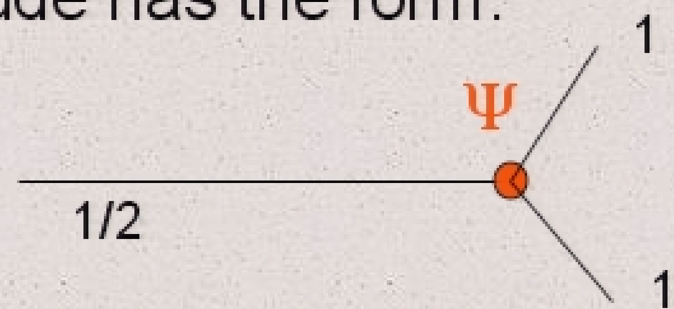
$A^{1/2\;1/2\;1/2}{}_{111}$



The standard LQG fermion amplitude has the form:



F[1]

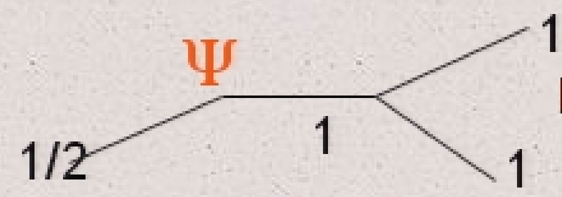


We have to do this twice to reproduce the pure gravity move:

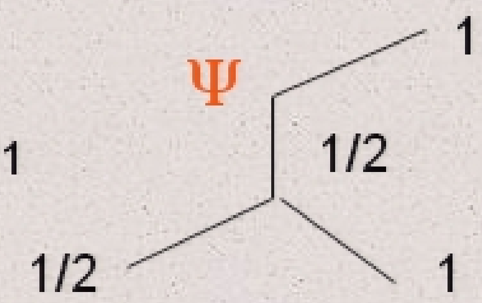
$$F[1]^2 = A^{1/2\;1/2\;1/2}{}_{111}$$

j

Lets look at this in detail:



$\Rightarrow A^{1/2\ 1/2\ 1/2}_{\ 111}$



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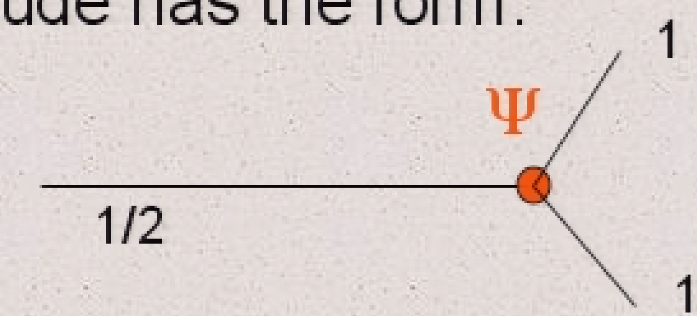
$\Rightarrow F[1]$



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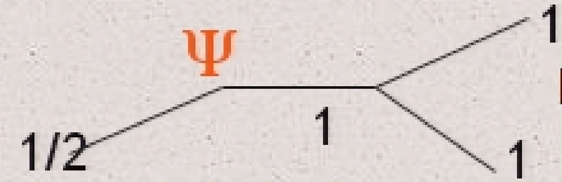
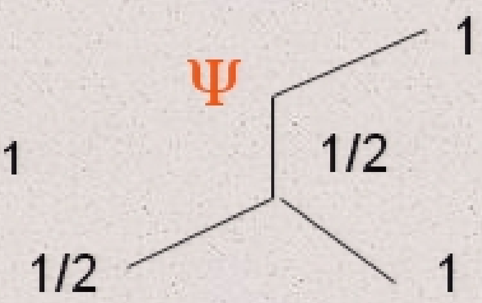


$\Rightarrow A^{1/2\ 1/2\ 1/2}{}_{111}$



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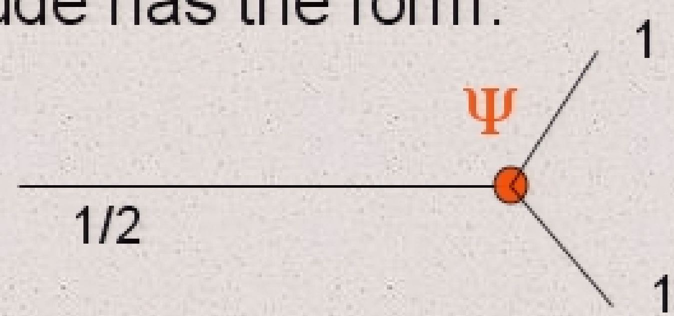

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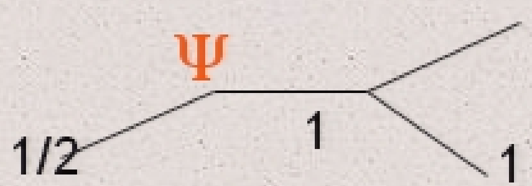

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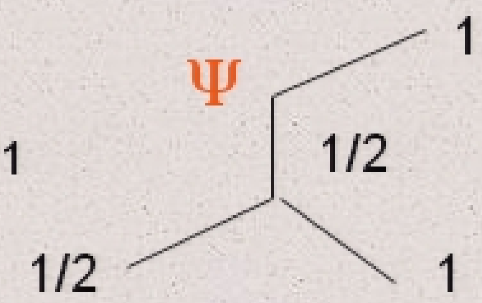

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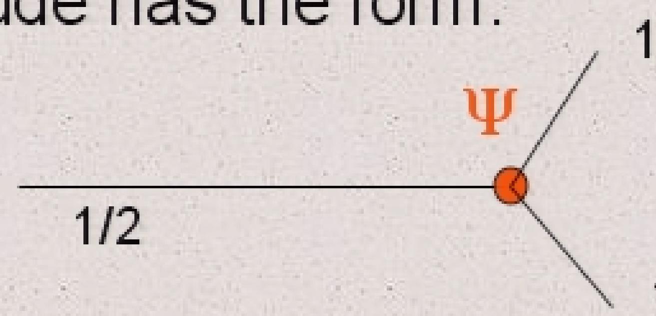

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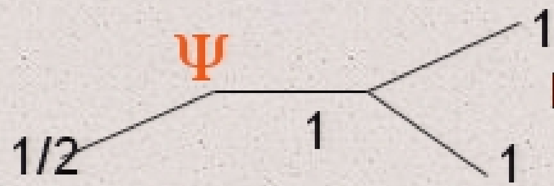

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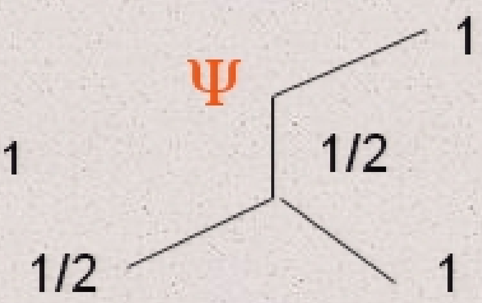

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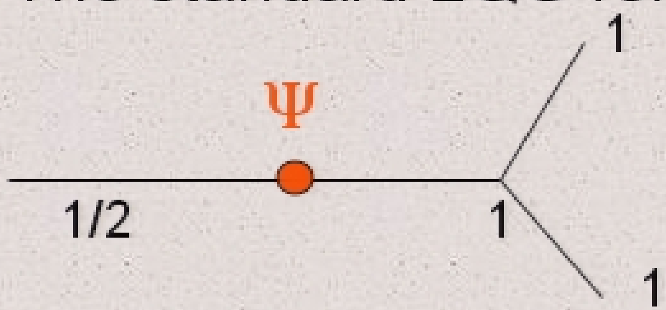

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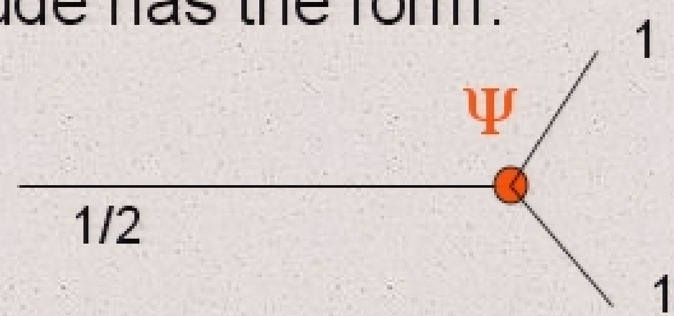

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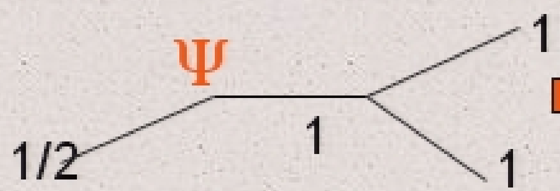
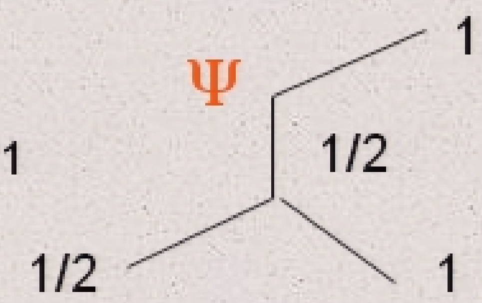


$\Rightarrow A^{1/2\ 1/2\ 1/2}{}_{111}$



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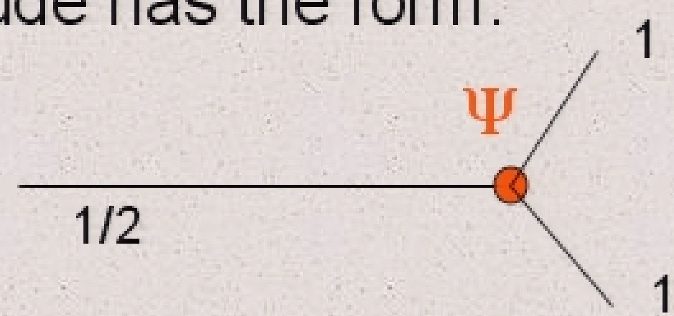

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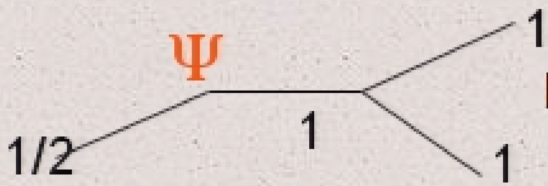
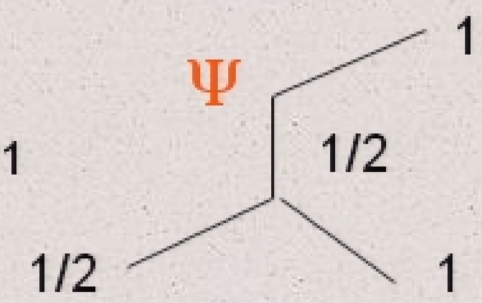


$$\rightarrow A^{1/2\ 1/2\ 1/2}{}_{111}$$



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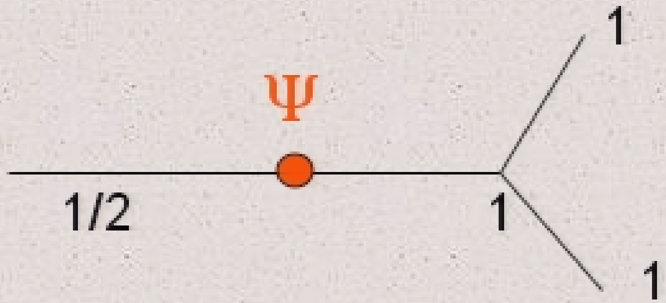

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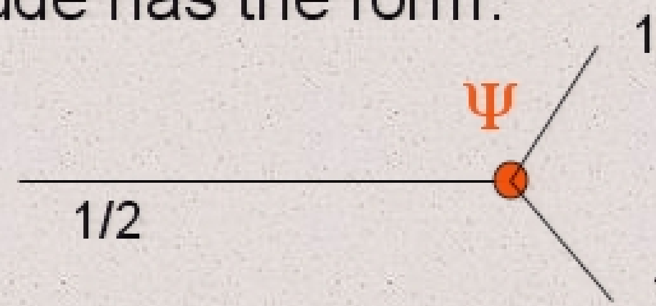

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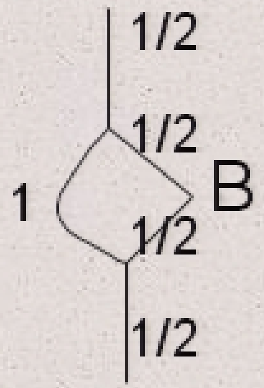
Interactions come from moves that are local microscopically, but non local macroscopically:

A spin-1 boson:



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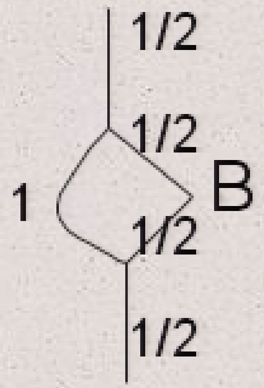

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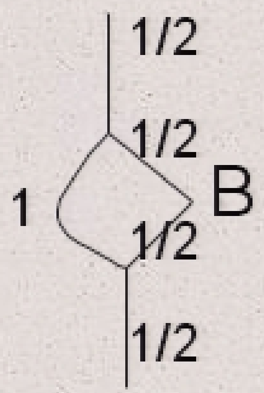

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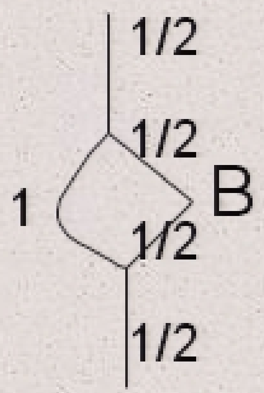

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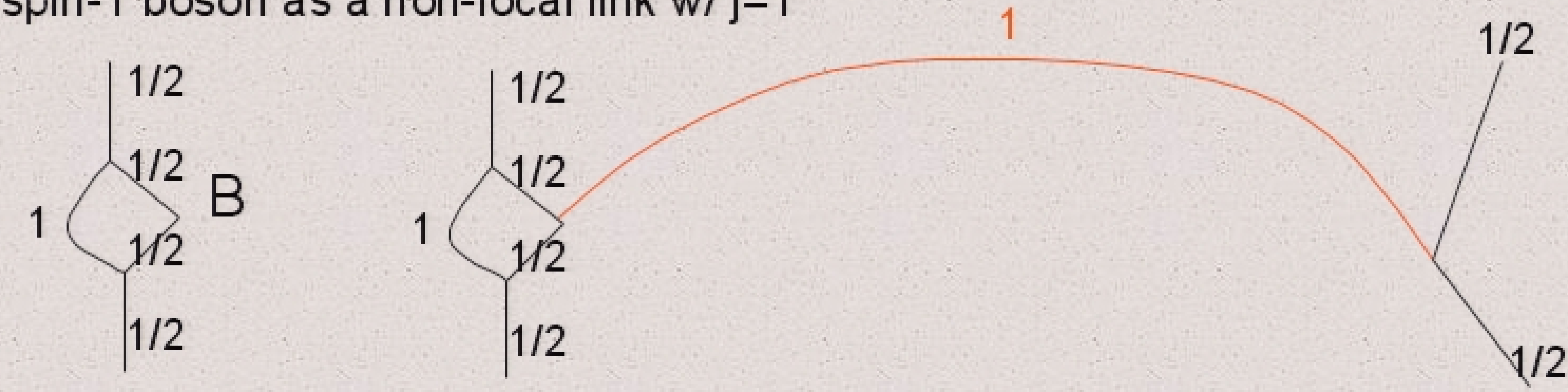

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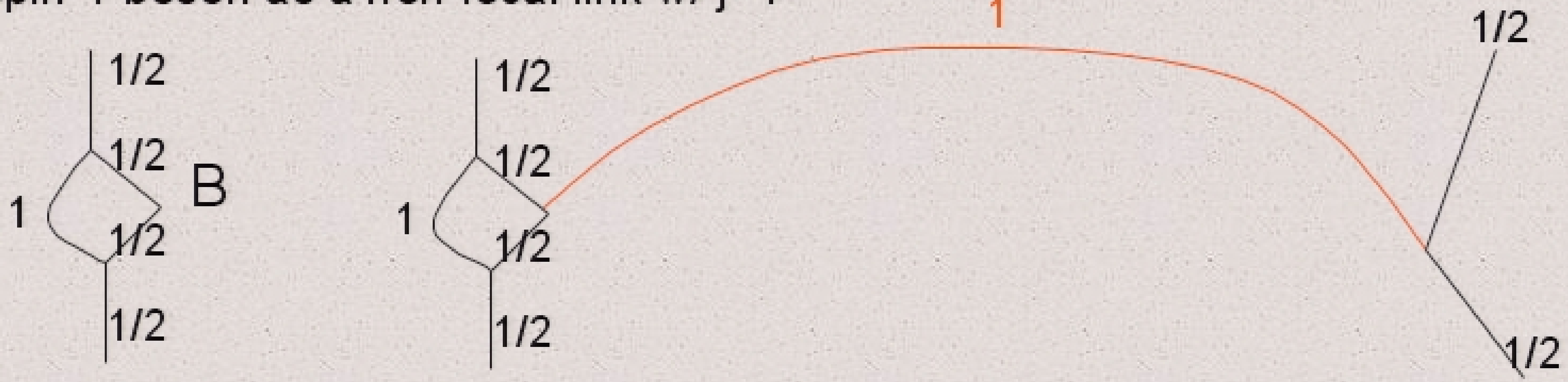

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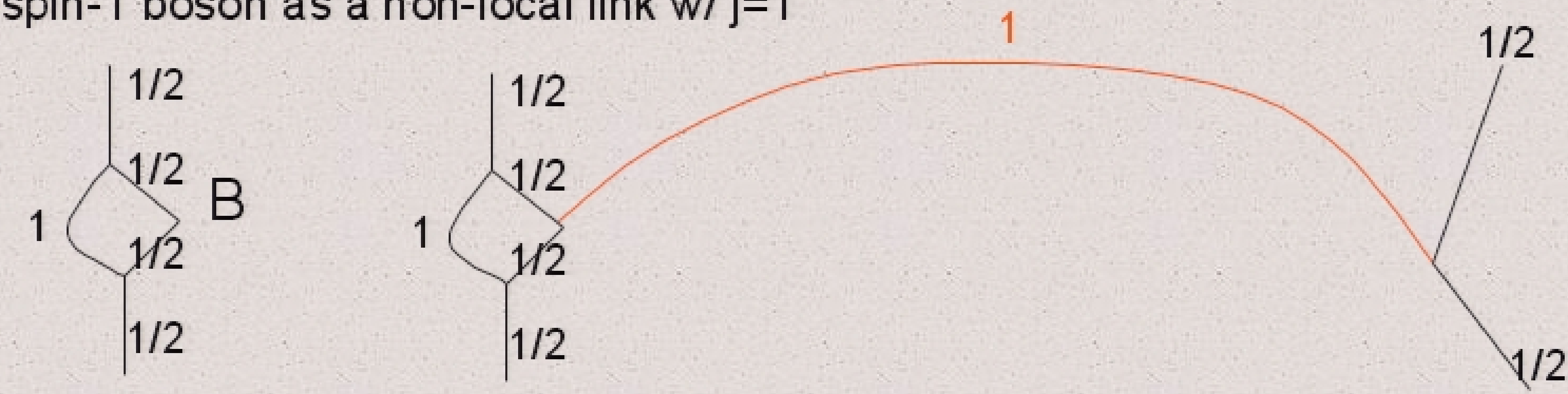

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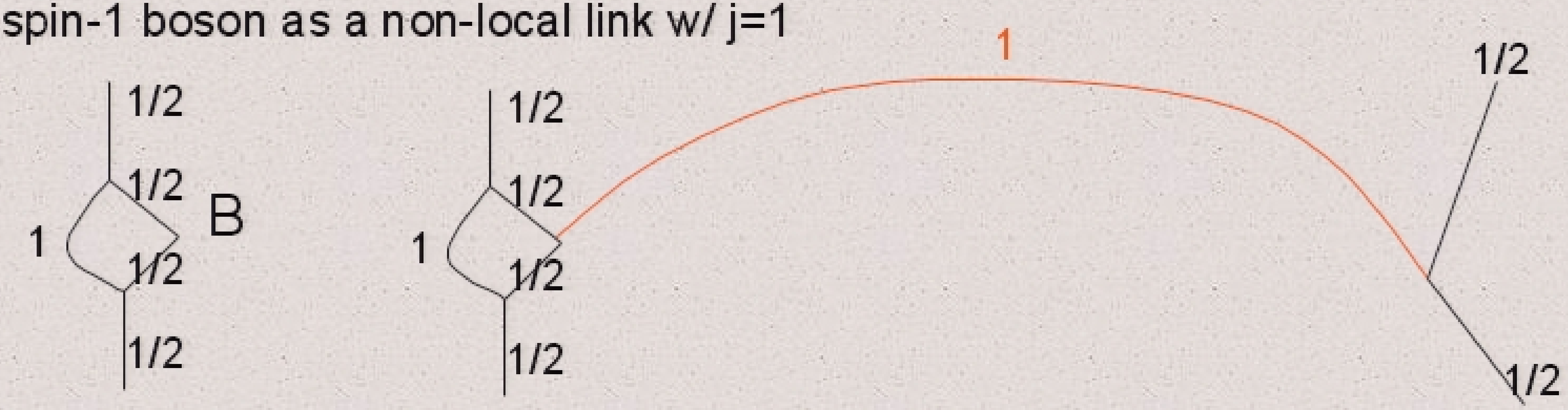

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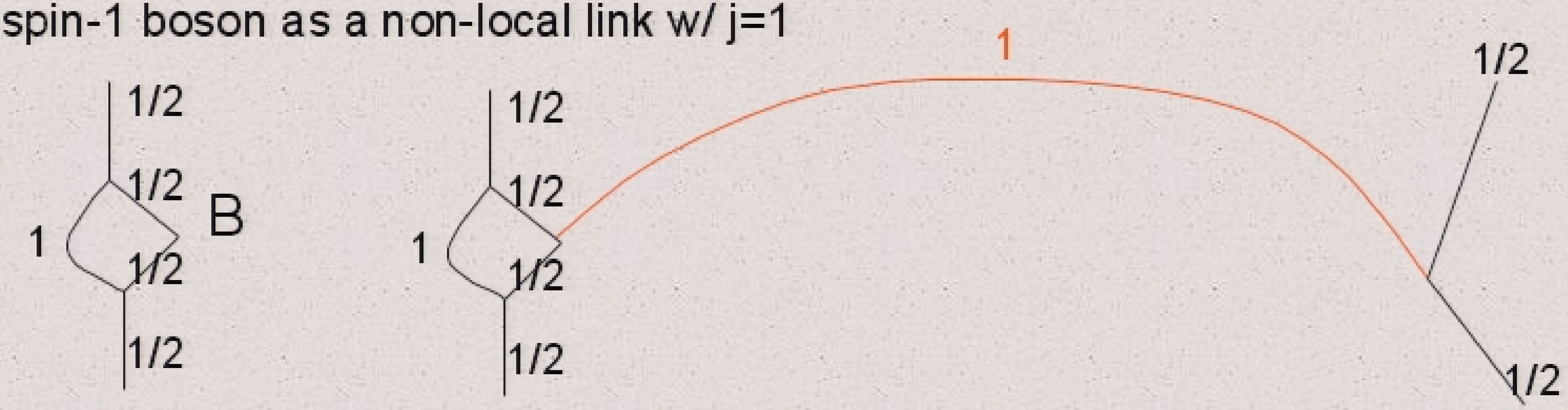

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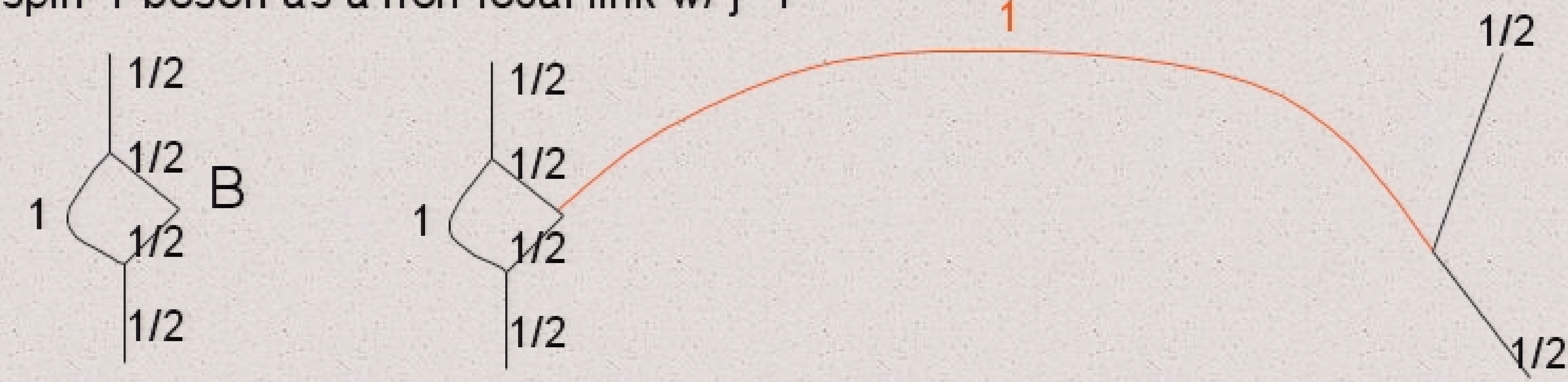

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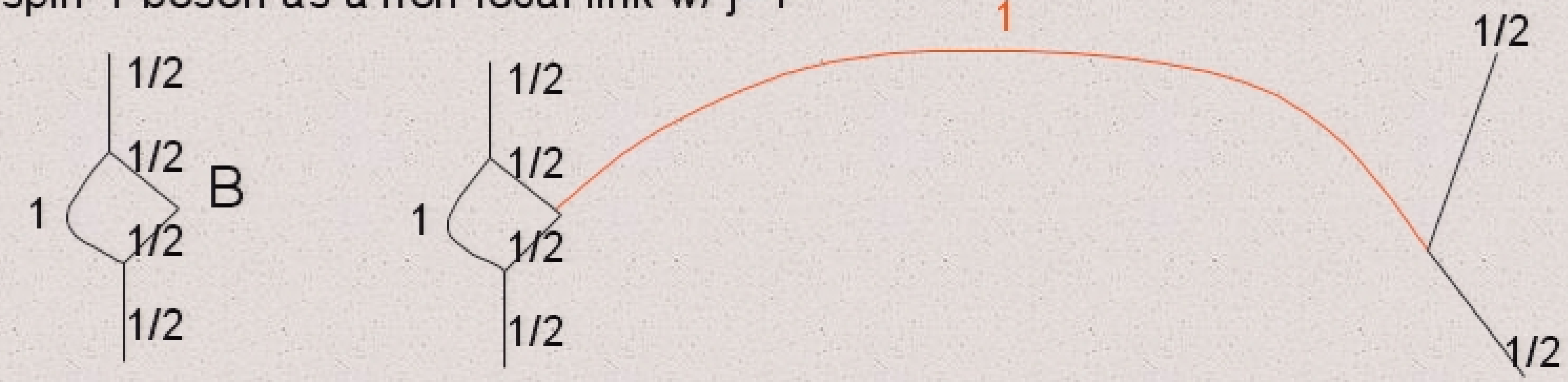

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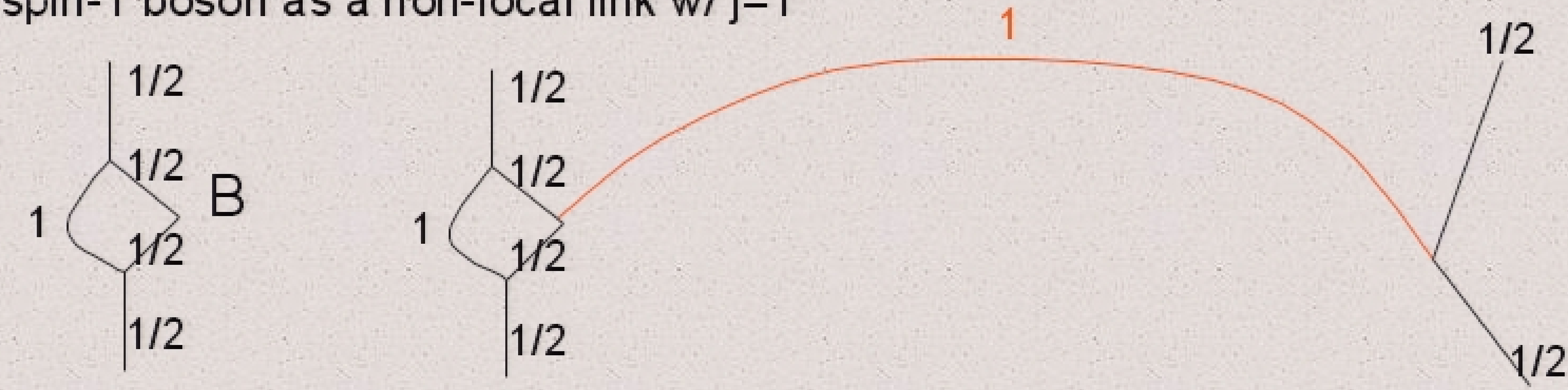

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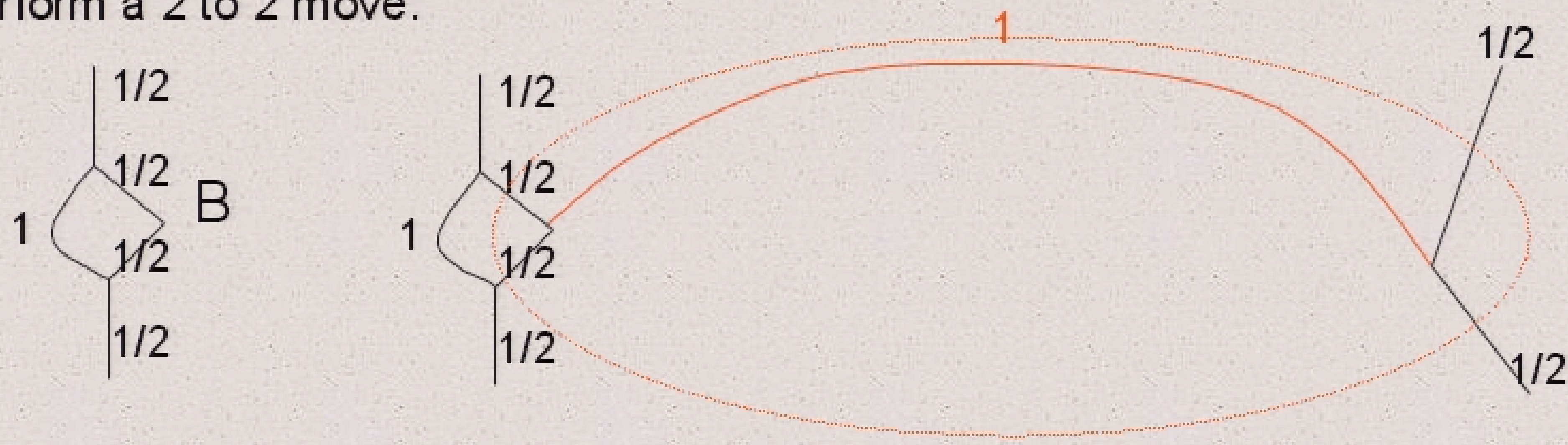

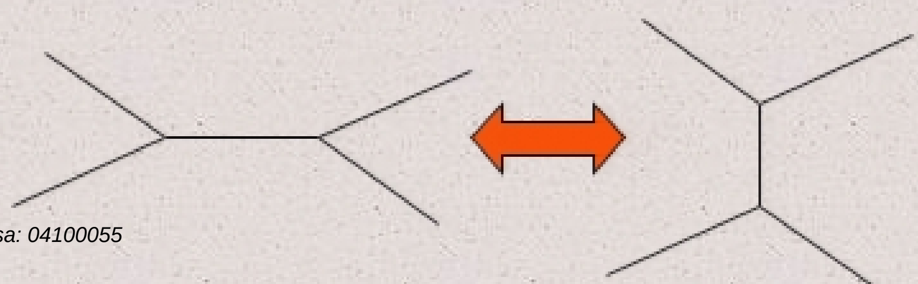

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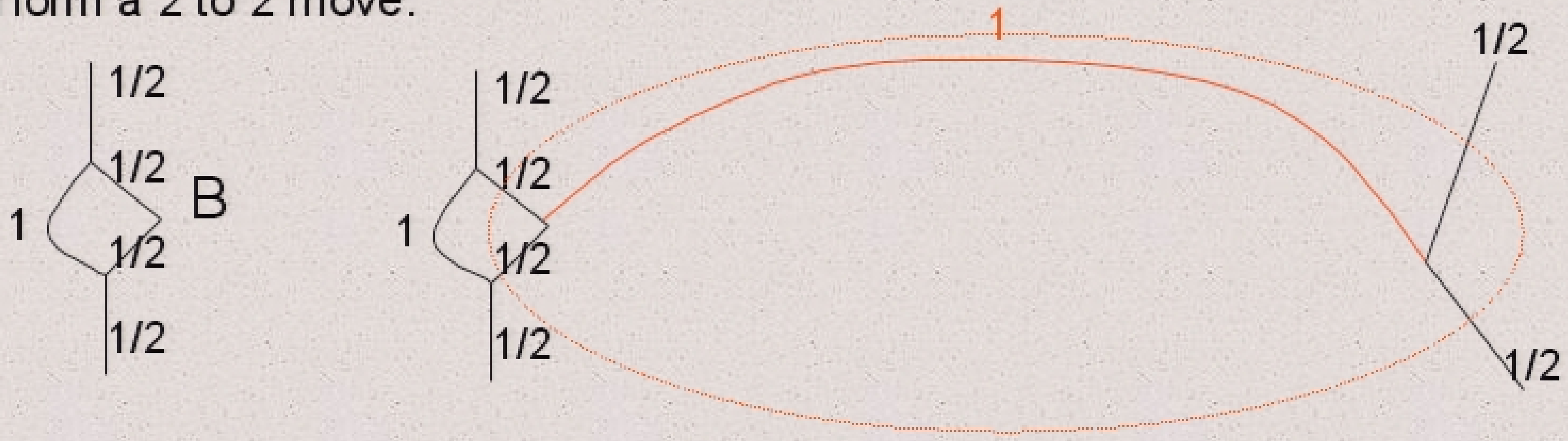

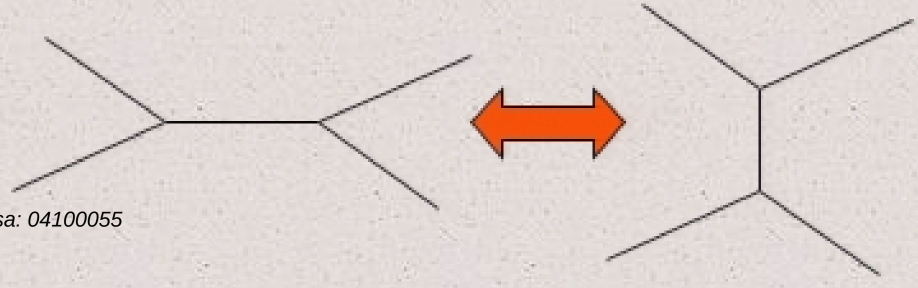

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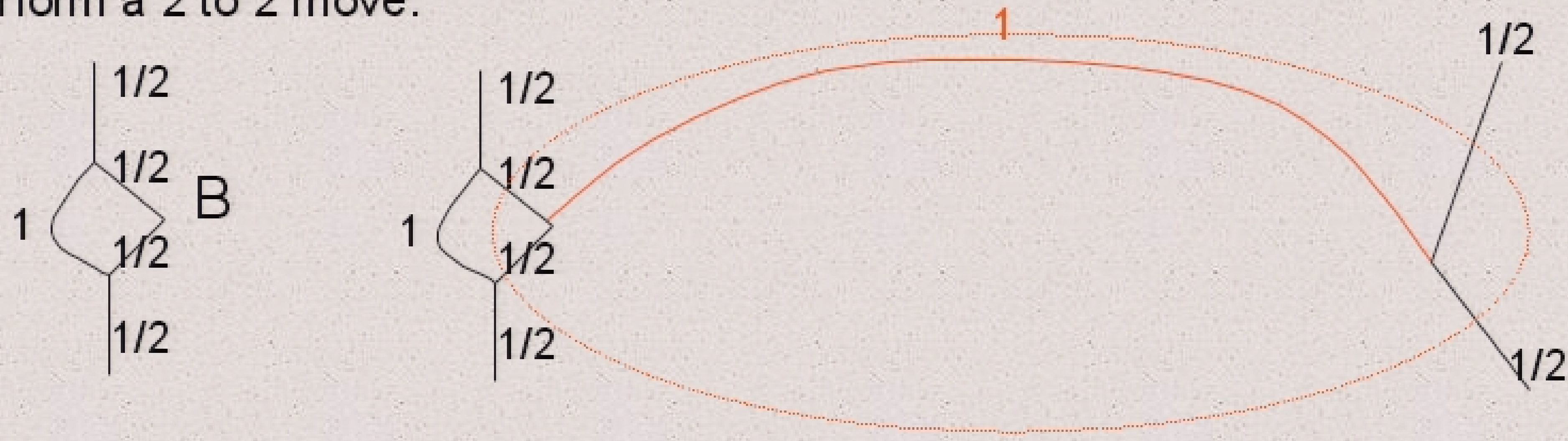

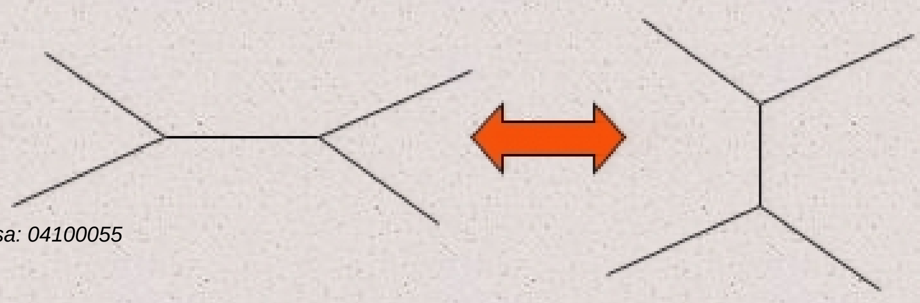

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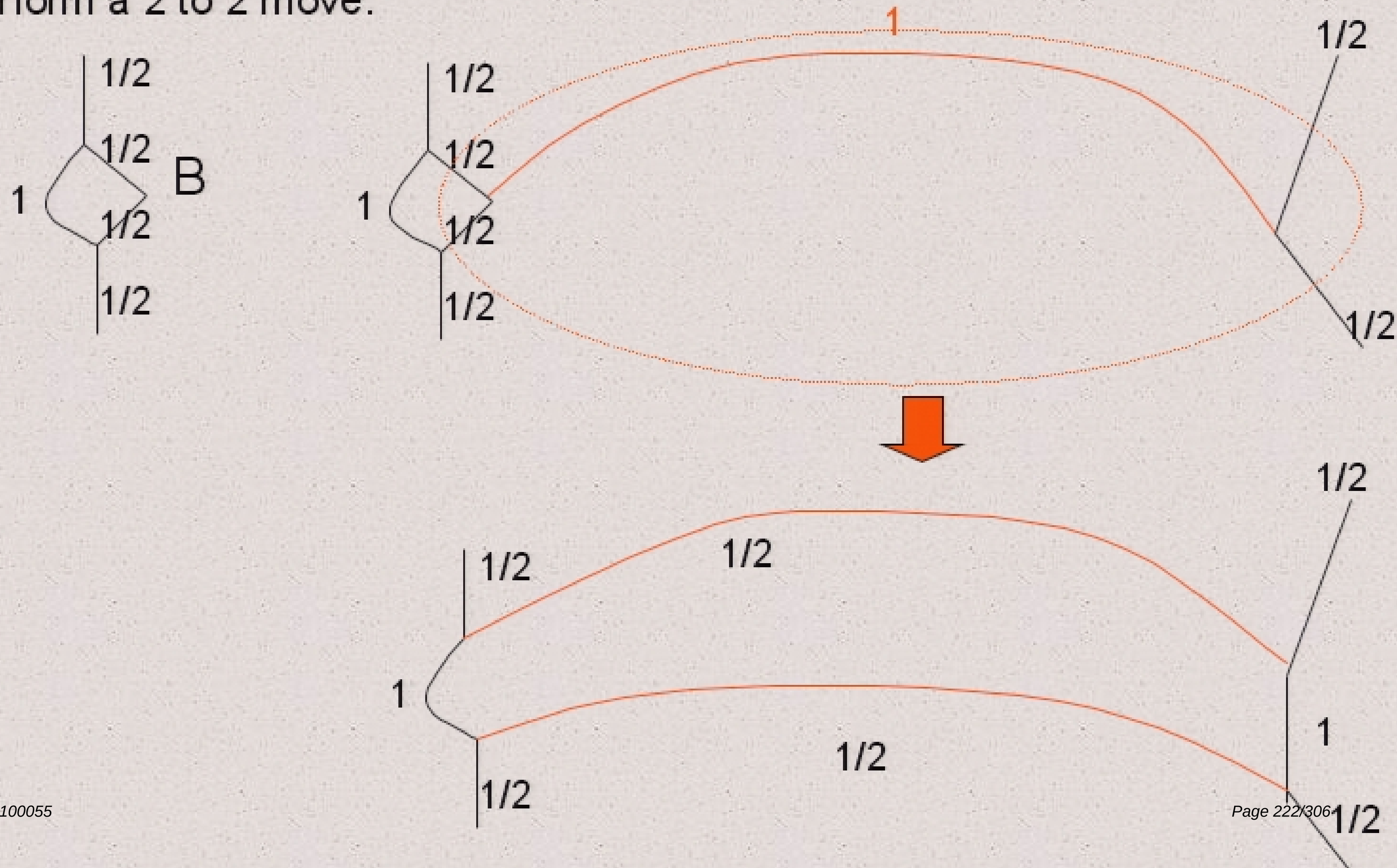

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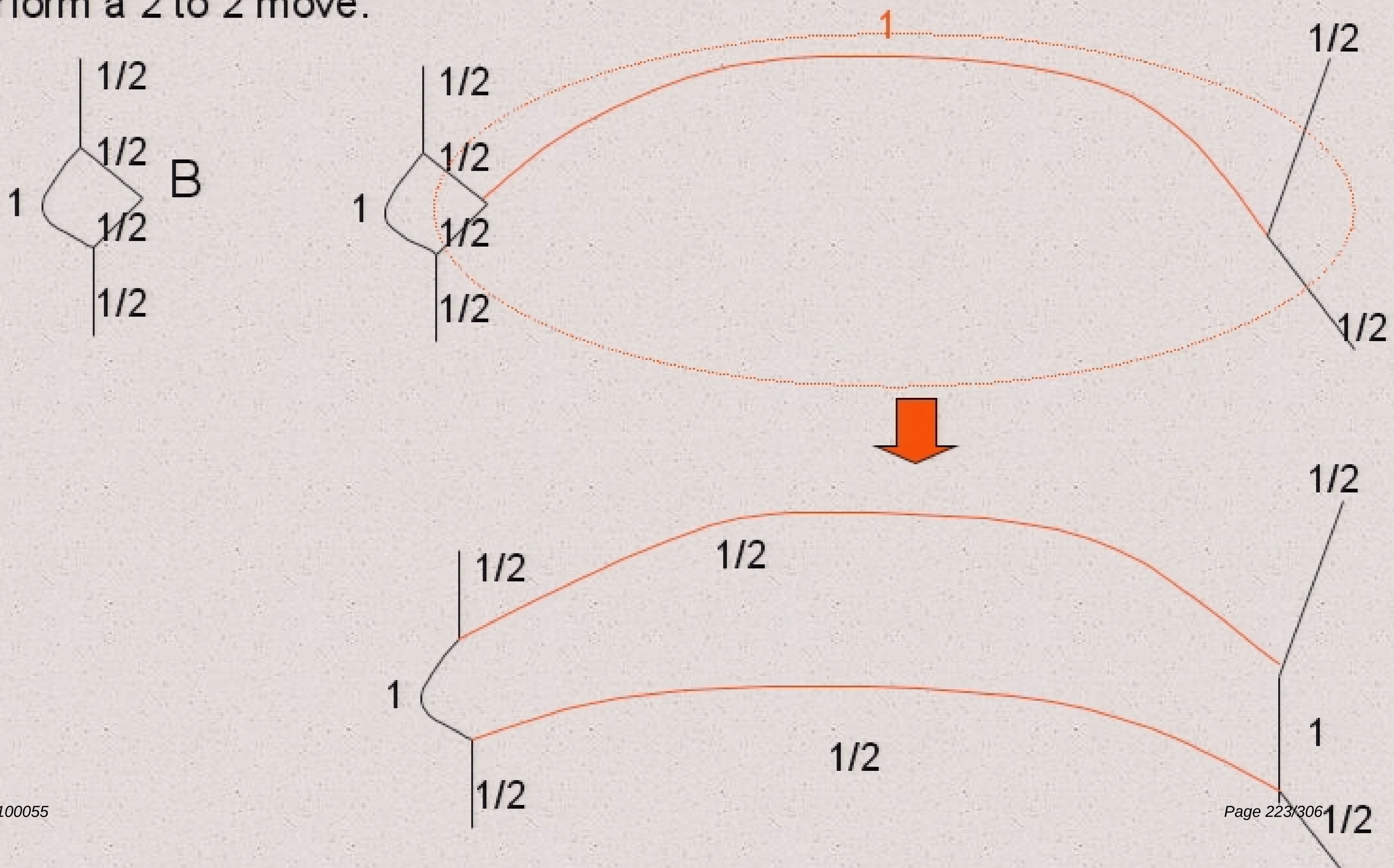

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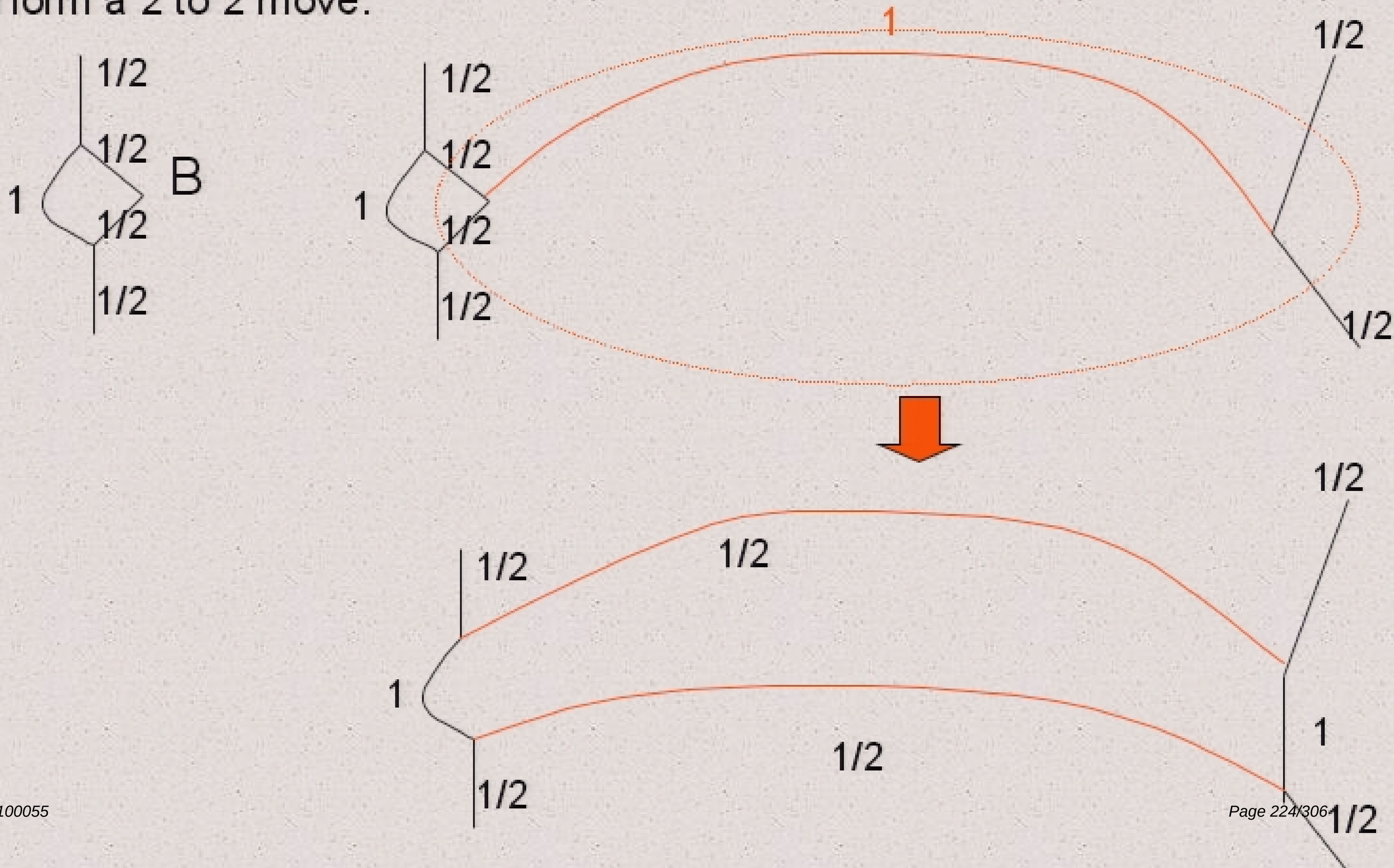

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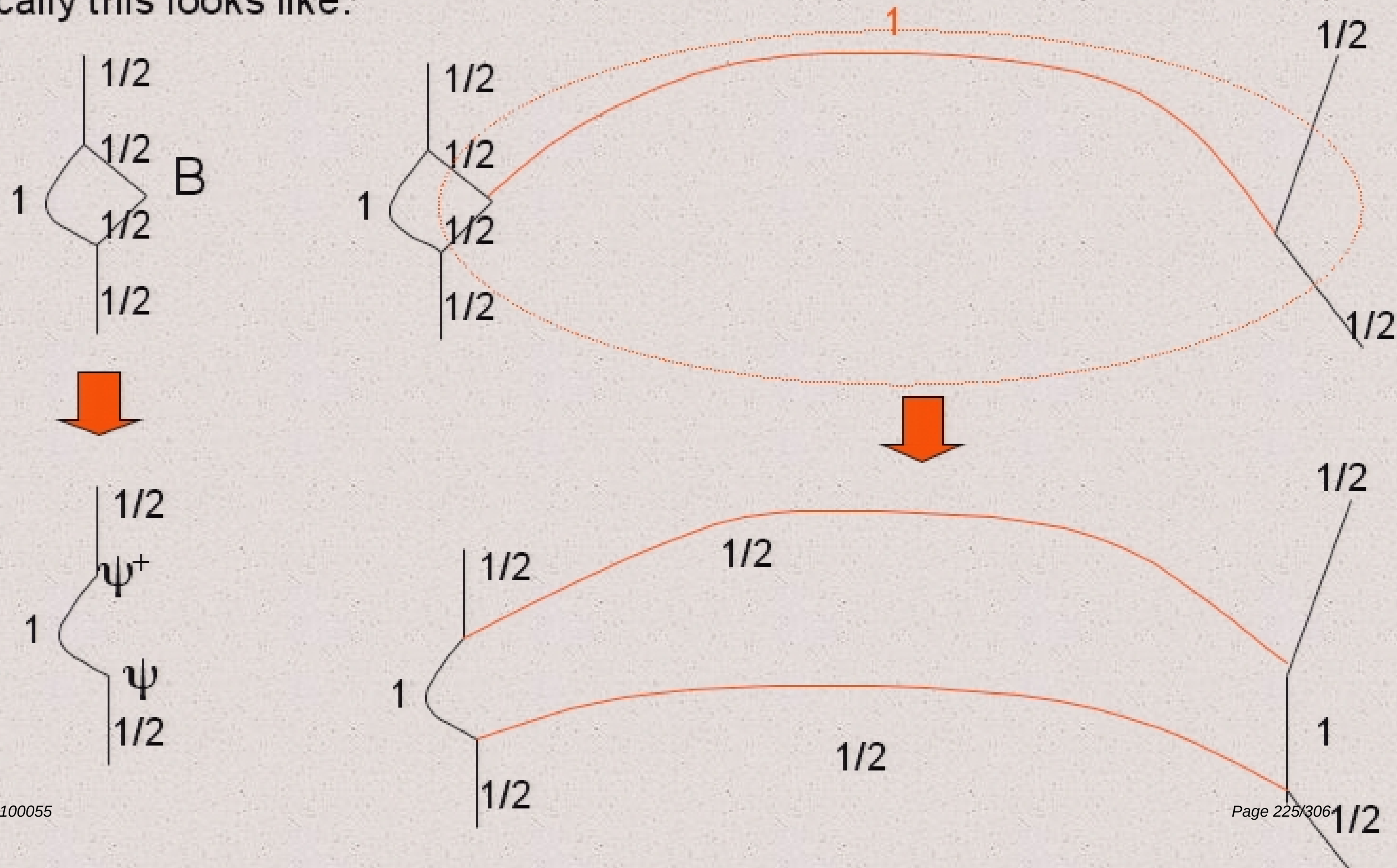

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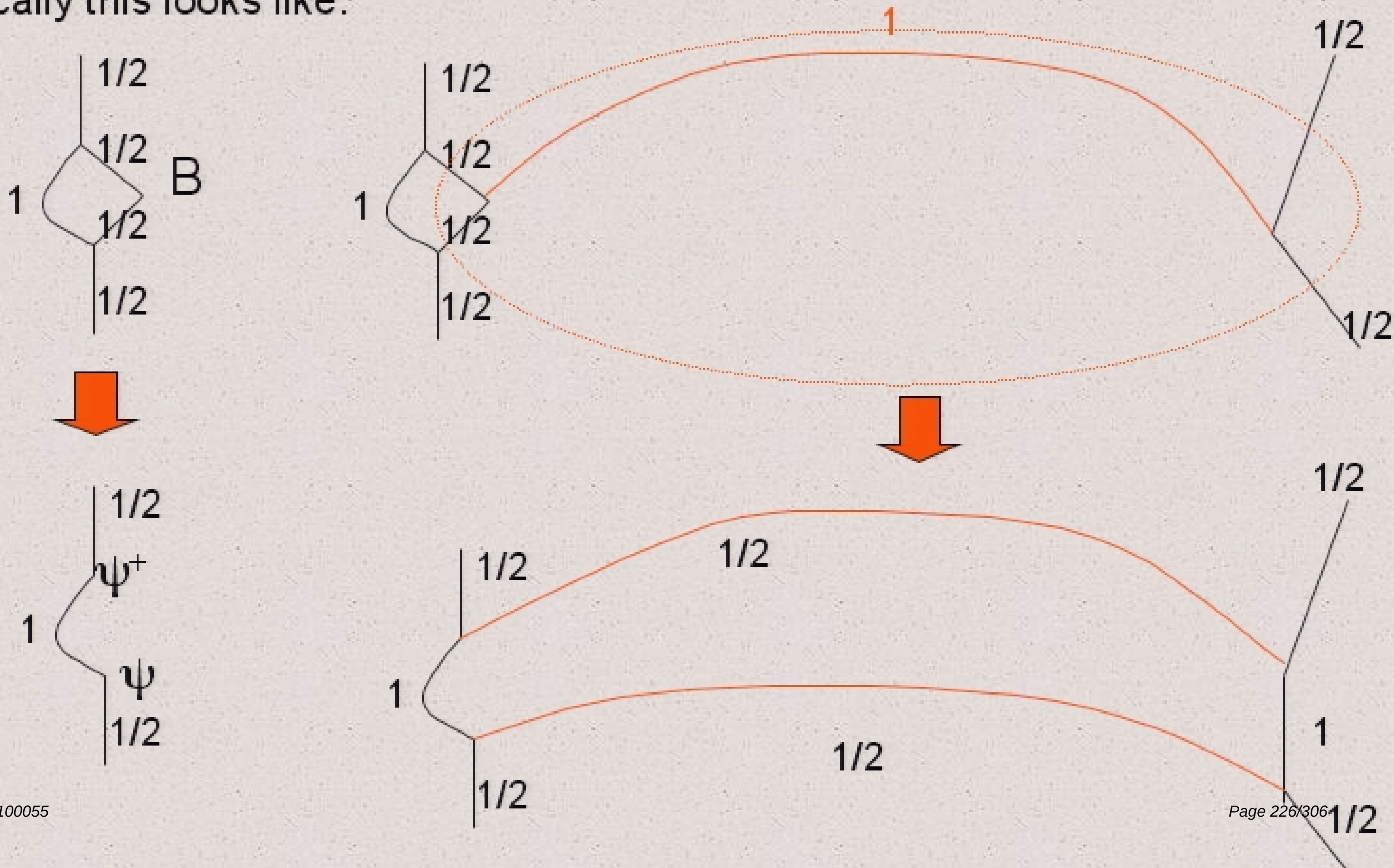

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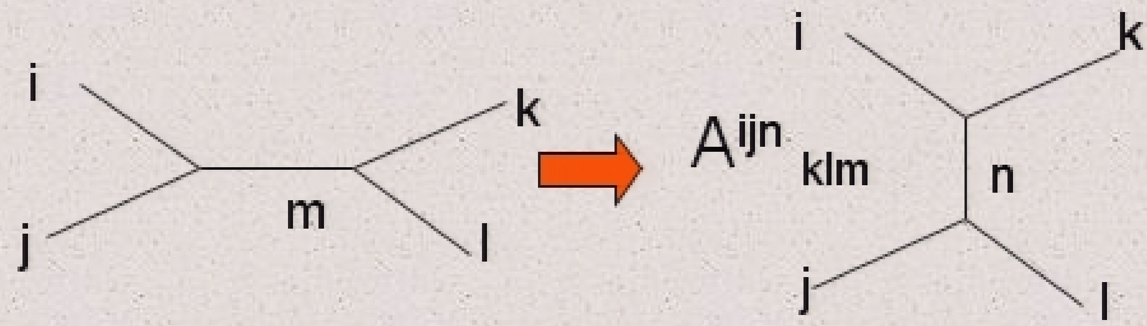

The amplitude for matter interaction comes from the pure gravity evolution amplitude.

$$\mathrm{Amp}_{B \to \psi+\ \psi} = A^{1/2\ 1/2/1}{}_{1/2\ 1//2\ 1}$$

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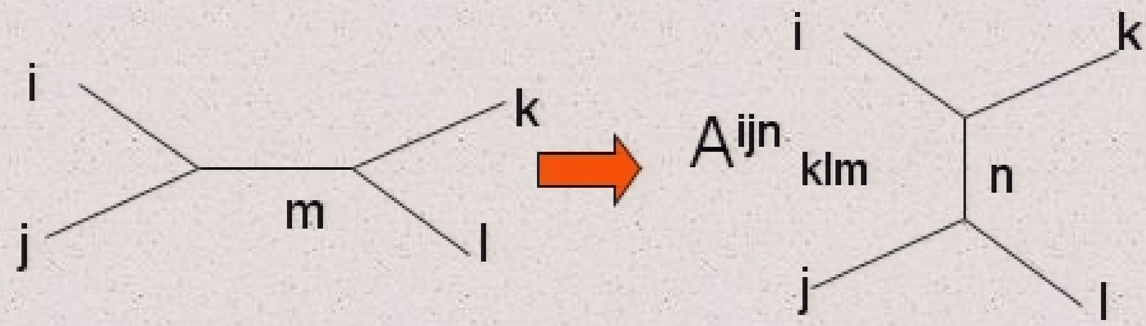

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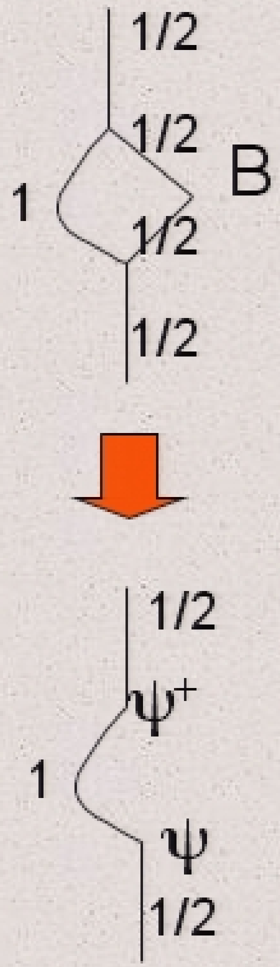

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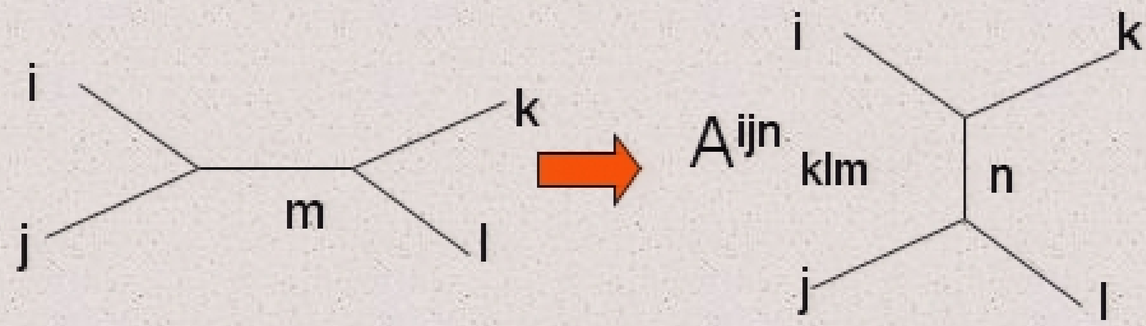

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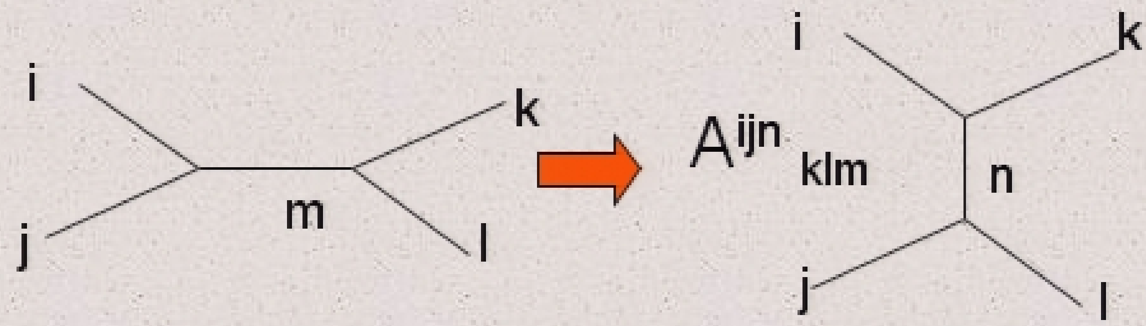

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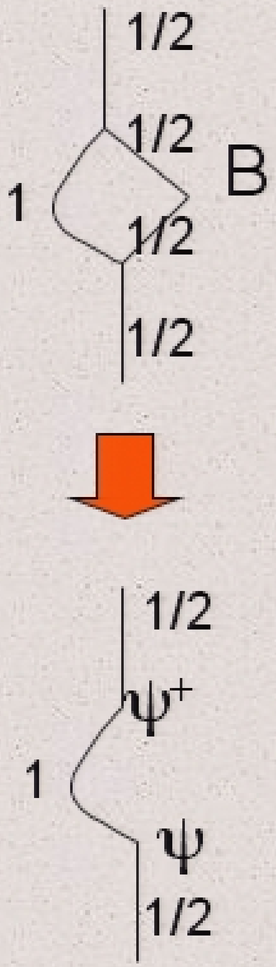

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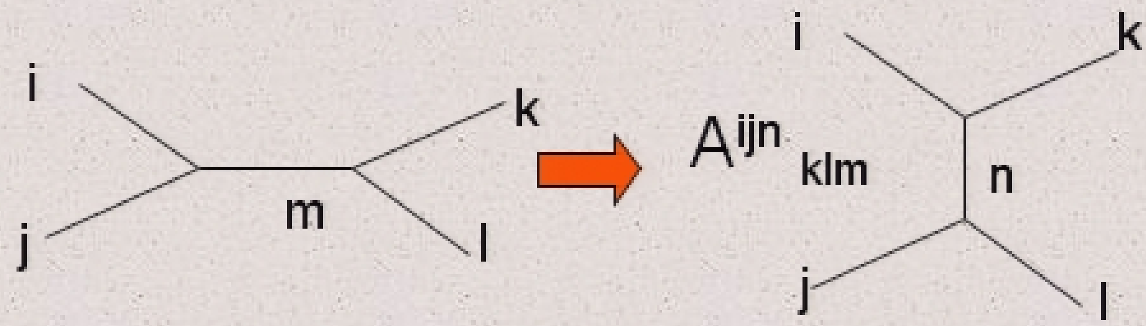

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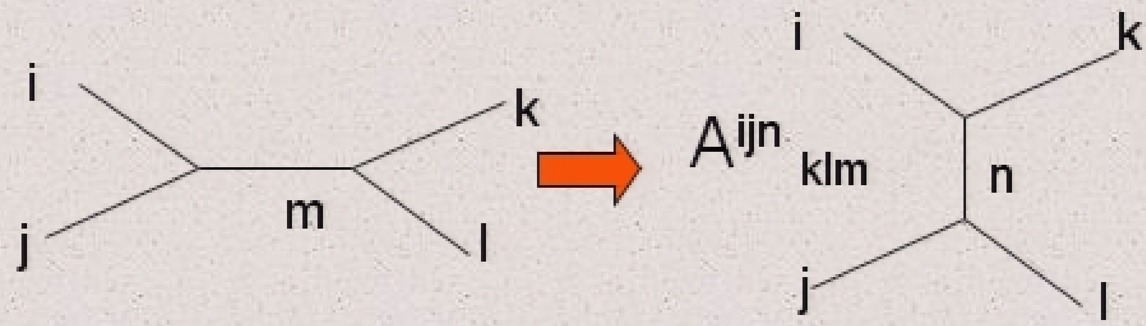

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- Works also when coupling to gauge fields are included. Just label edges by reps of SU(2) X G.

- Pair creation possibly implies spin-statistics connection.

  Dowker, Sorkin, Balachandran.....

- $CPT_{gravity} \Rightarrow CPT_{matter}$ same for CP, T etc

- *Does CP breaking in matter imply CP breaking in gravity?*

- We get a tower or particles of increasing spin, just like Regge trajectories in string theory.

- This gives a unification in which fermions appear in fundamental representations of gauge groups- unlike SUSY where they appear in adjoint reps- but like nature

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$N_{nodes} \sim 10^{180}$ $N_{nll} \sim N_{baryon} \sim 10^{80}$

$P = N_{nnl} / N^2_{nodes} \sim 10^{-280}$

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Evidence for non-local effects in very low energy astrophysics:

The Tully Fischer Relation:

- Galaxies have flat rotation curves, with velocity V.
- Total luminosity L

astro-ph/0204521

$$C\,L = V^a \qquad a = 3.9 \pm 0.2$$

- K= L/M (M-total mass)

$$CK\,M = V^4$$

- *CK should be prop to G*
- $CK = Ga_0$

$$a_0 = 1.2\ 10^{-8}\ cm/sec^2$$
$$= \sqrt{\Lambda}\ c^2/6$$

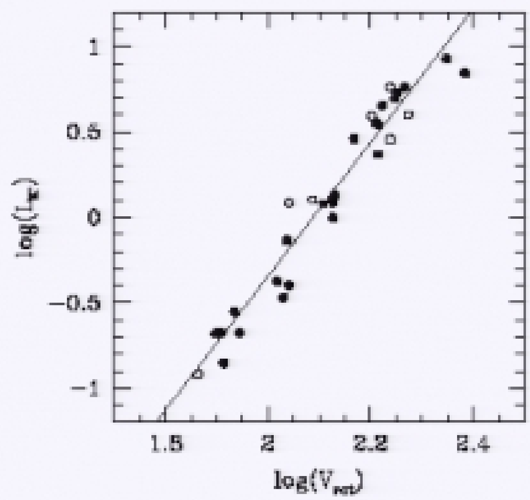

Figure 2: The near-infrared Tully-Fisher relation of Ursa Major spirals ((Sanders & Verheijen 1998)). The rotation velocity is the asymptotically constant value. The velocity is in units of kilometers/second and luminosity in $10^{10}\ L_\odot$. The unshaded points are galaxies with disturbed kinematics. The line is a least-square fit to the data and has a slope of 3.9 ± 0.2

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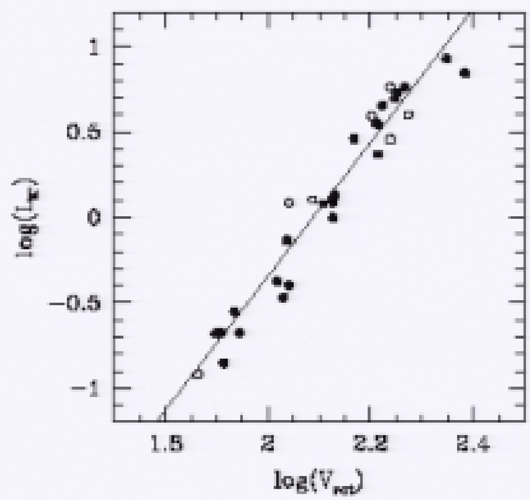

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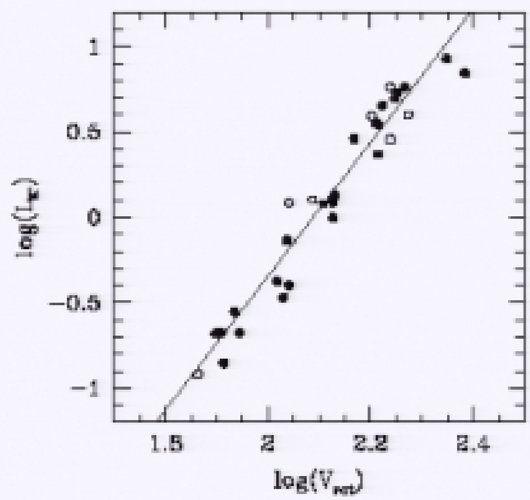

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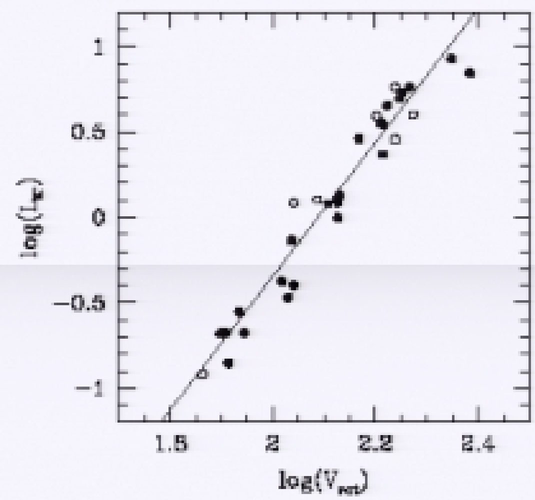

Figure 2: The near-infrared Tully-Fisher relation of Ursa Major spirals ((Sanders & Verheijen 1998)). The rotation velocity is the asymptotically constant value. The velocity is in units of kilometers/second and luminosity in $10^{10}\ L_\odot$. The unshaded points are galaxies with disturbed kinematics. The line is a least-square fit to the data and has a slope of 3.9 ± 0.2

Evidence for non-local effects in very low energy astrophysics:

The Tully Fischer Relation:

- Galaxies have flat rotation curves, with velocity V.
- Total luminosity L

astro-ph/0204521

$$C\,L = V^{a} \qquad a = 3.9 \pm 0.2$$

- K= L/M (M-total mass)

$$CK\,M = V^{4}$$

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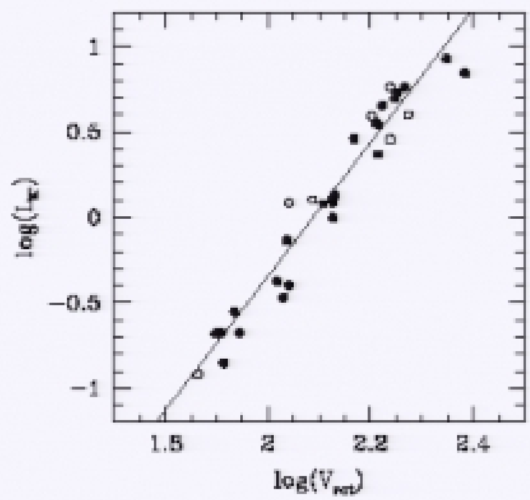

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$$a < a_0 \qquad a = (a_N a_0)^{1/2}$$

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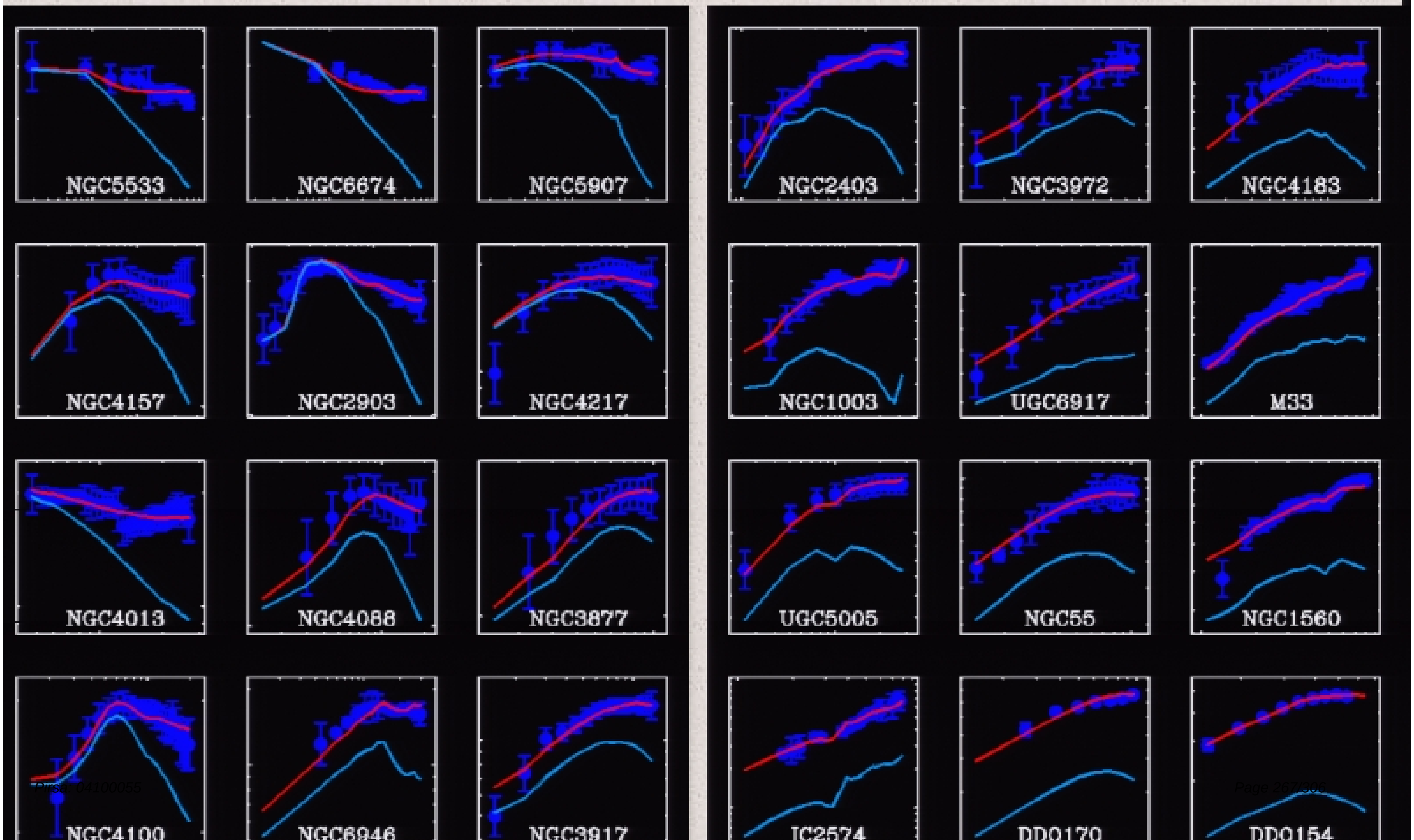
The MOND potential:

$$\phi_{MOND}(r) = \sqrt{GMa_0}\left[\ln(\frac{r}{r_0}) - 1\right]$$


NGC5533
NGC6674
NGC5907
NGC2403
NGC3972
NGC4183
NGC4157
NGC2903
NGC4217
NGC1003
UGC6917
M33
NGC4013
NGC4088
NGC3877
UGC5005
NGC55
NGC1560
NGC4100
NGC6946
NGC3917
IC2574
DDO170
DDO154

- The MOND formula does embarrassingly well!

- Dark matter calculations do not do nearly as well:
  - Don't account for Tully-Fischer
  - Have cusps, dark matter should dominate in the centers of galaxies, but in the data they don't

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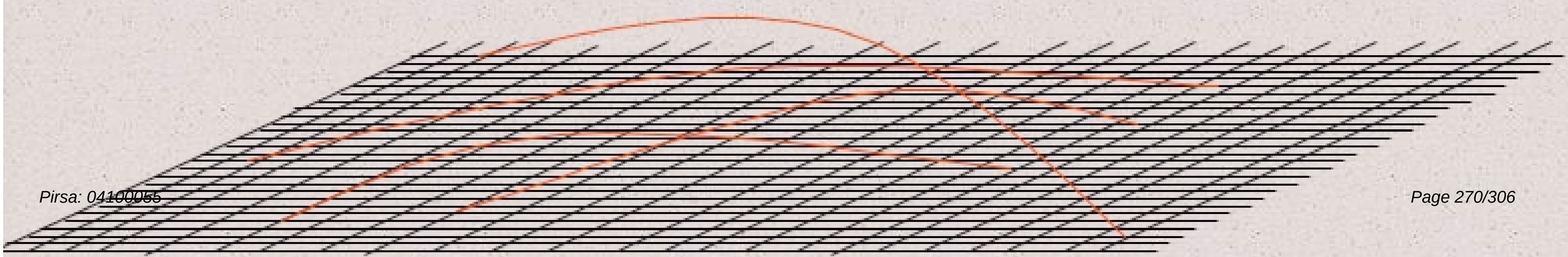
Bimetrics for graphs:

r_{nm} = distance between n and m in metric q_{ab}.

•The weave can be chosen so the graph metric matches r_{nm}

P(r) probability that nodes n and m are connected if they are a distance r apart in the metric q_{ab}

⇒ d (r) minimal expected graph distance between two nodes r apart in q_{ab}.



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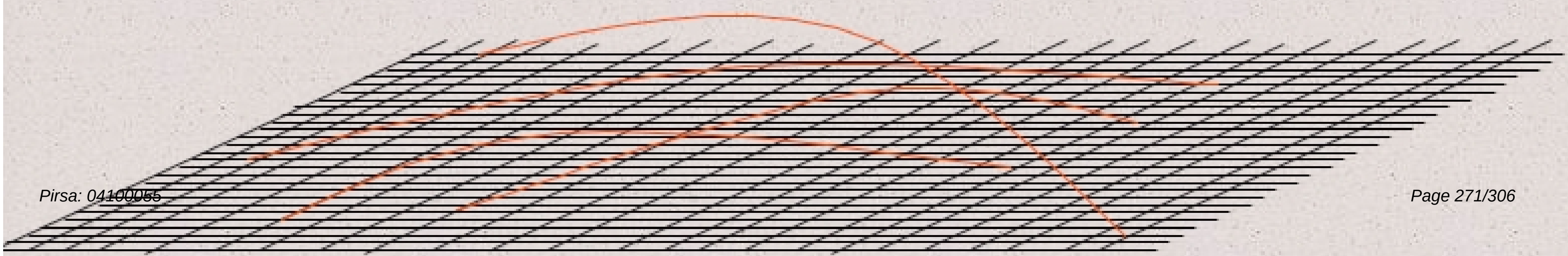
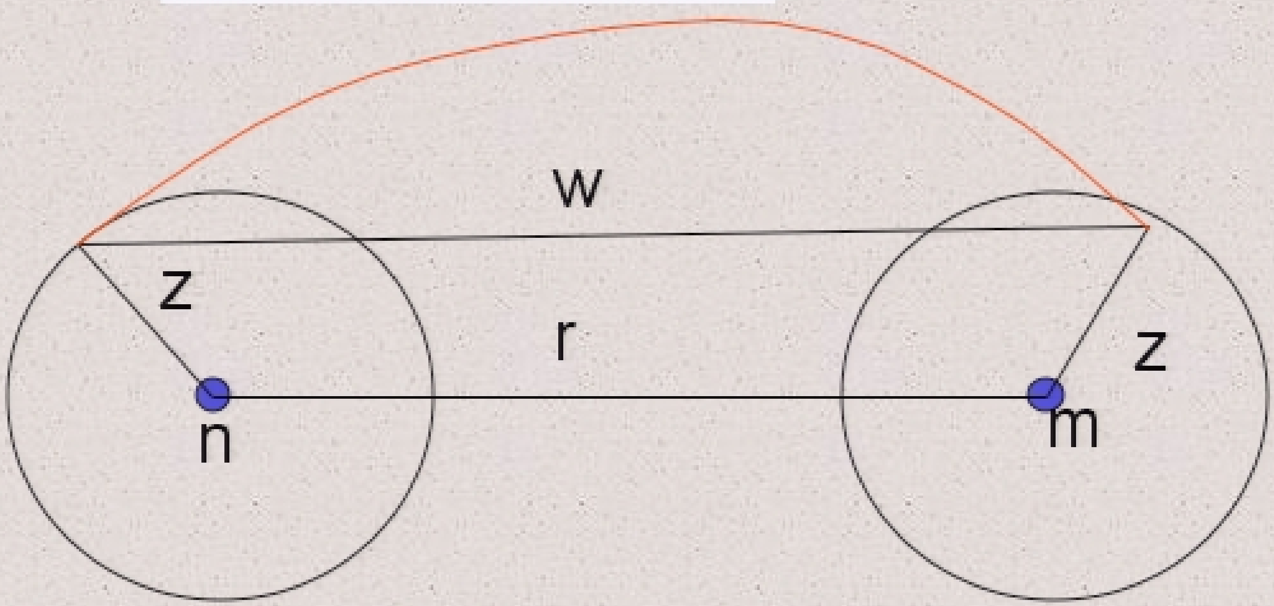


Prob of path w one jump: $\left(\frac{4\pi^2 z^2}{l_p^2}\right)^2 P(r)$ z<r w ~r

We want z st the prob from a region around n and m are so connected. This means $N\left(\frac{4\pi^2 z^2}{l_p^2}\right)^2 P(r) = 1$



This gives

$$z(r) = \frac{l_p}{2\pi}\frac{1}{(NP(r))^{1/4}}$$

When this is true

$$\bar{d}(r) = 2z(r) + 1$$

This tells us the relationship between P(r) and d(r) $\bar{d}(r) = \frac{l_p}{\pi}\frac{1}{(NP(r))^{1/4}}$

•*Our physical ansatz requires that* $\varphi_{MOND}(r) = -GM/d(r)$

•*Mond:*

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So there is a wormhole distribution that leads to MOND

N=1 ➡ $P \sim 10^{-216}$

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- *Particles of all spins (like strings!!!)*
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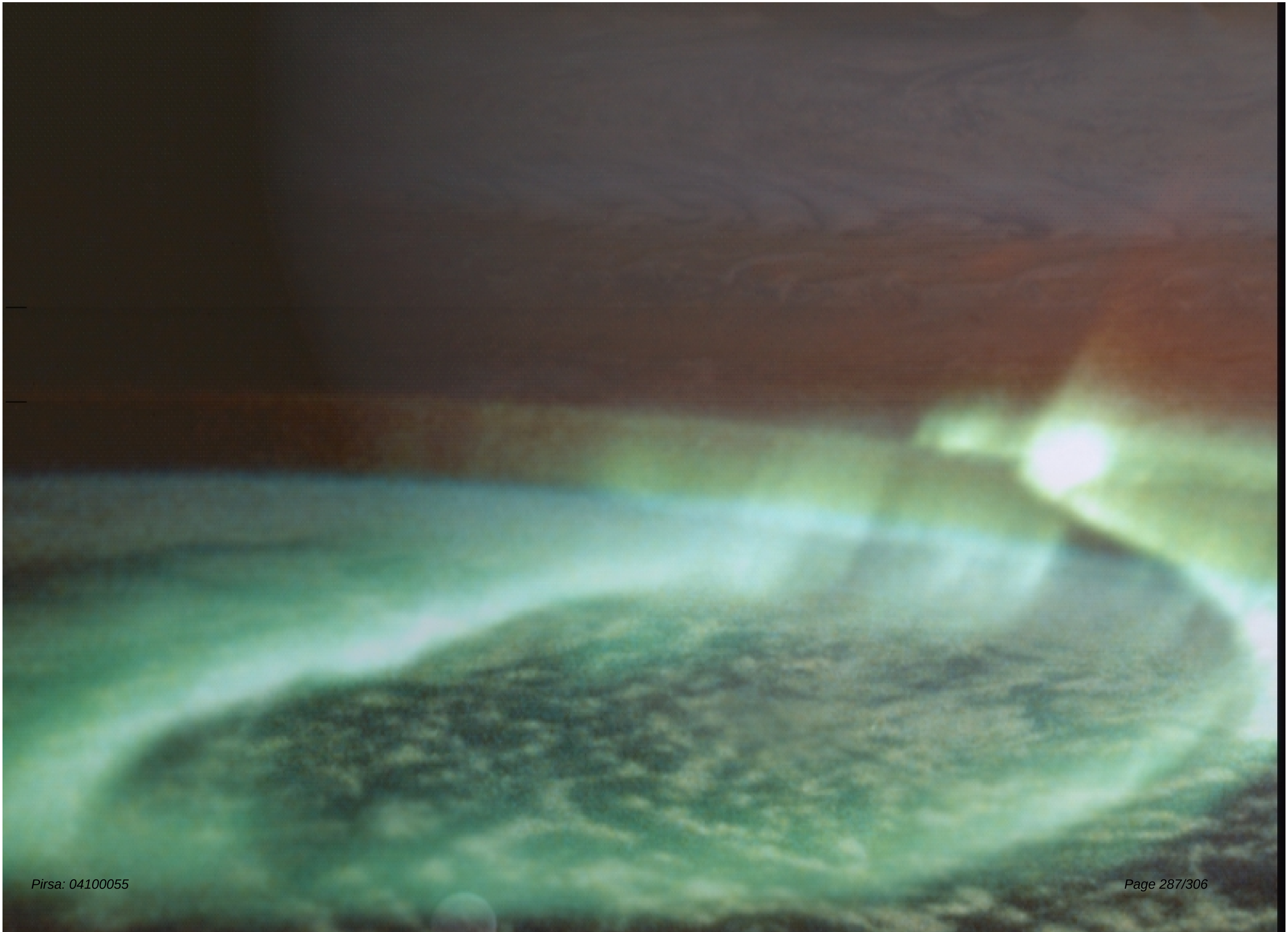

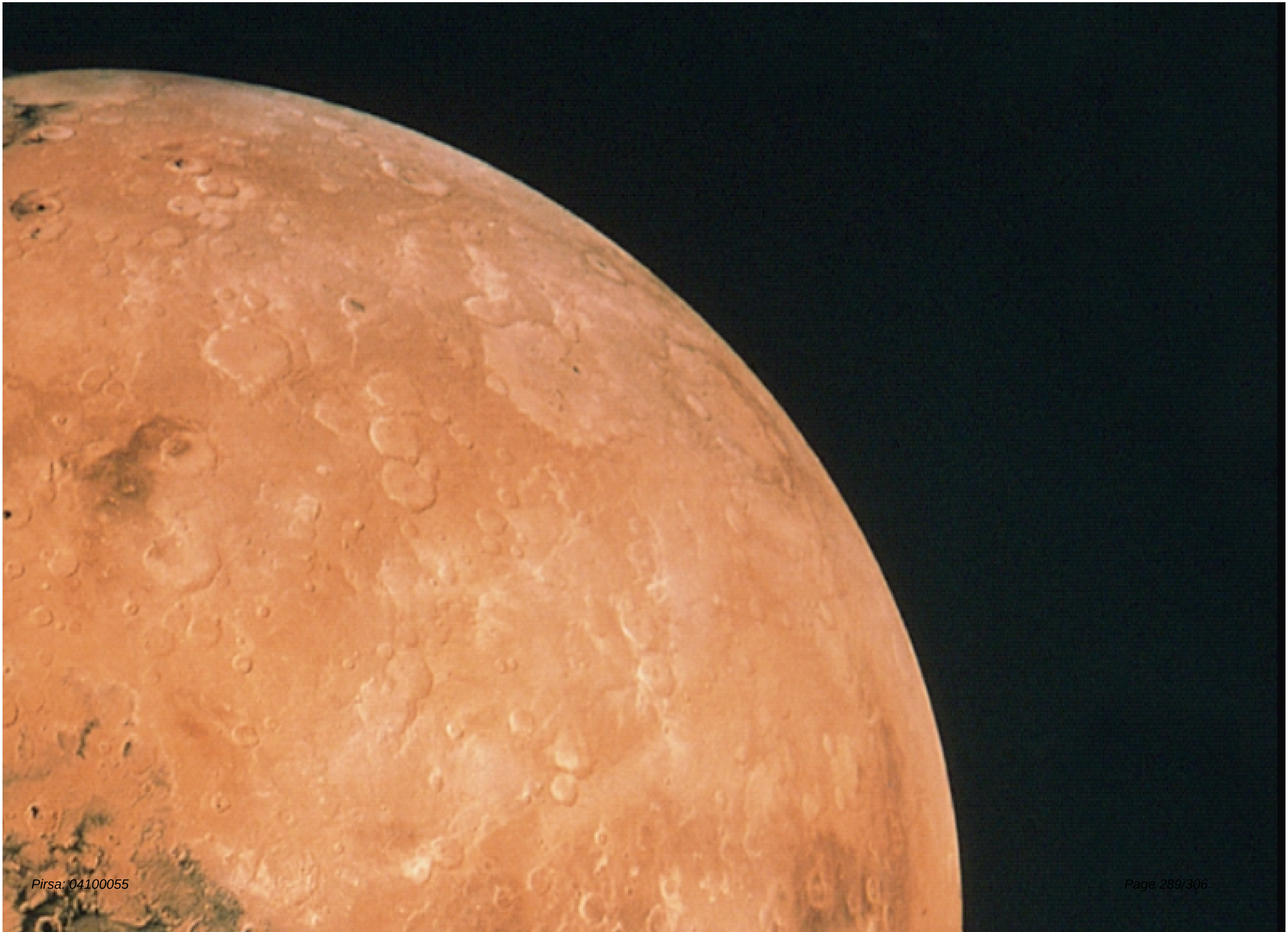

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To explain charged matter: $P \sim 10^{-280}$

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