Introduction To Neutrinos

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March 15, 2007

The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses!

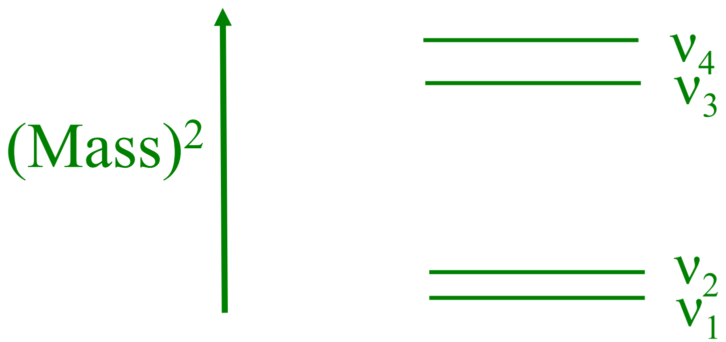
Leptons mix!

These discoveries come from the observation of ***neutrino flavor change (neutrino oscillation)***.

The Physics of Neutrino Oscillation

Suppose There Are ***Neutrino Masses***

Then there is some spectrum of neutrino mass eigenstates ν_i:



Mass $(\nu_i) \equiv m_i$

Suppose There Is ***Leptonic Mixing***

Then the neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

$(W \to e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau)$

are superpositions of the neutrinos of definite mass:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \, |\nu_i\rangle \quad .$$

ν_α: Neutrino of flavor $\alpha = e, \mu$, or τ

U: Unitary Leptonic Mixing Matrix

ν_i: Neutrino of definite mass m_i

Neutrino Flavor Change ("Oscillation")

Suppose a neutrino is born with flavor α and energy E.

$$\nu_\alpha = \sum_i U^*_{\alpha i} \nu_i \xrightarrow[\text{Distance L}]{} \sum_i U^*_{\alpha i} \nu_i e^{ip_i(E)L/\hbar} \equiv \nu(L) \neq \nu_\alpha$$

where $p_i(E) = \sqrt{E^2 - (m_i c^2)^2}/c$

The neutrino has evolved into a mixture of the flavors.

Often, only 2 neutrinos need to be considered.

Then –

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Mixing Angle (θ)

Then–

$$P(\nu_\alpha \rightarrow \nu_{\beta\neq\alpha}) = \sin^2 2\theta \left[\sin^2 1.27\, \Delta m^2(\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

Probability (P)

$$\Delta m^2 \equiv m_2^{\,2} - m_1^{\,2}$$

Neutrino oscillation

⇓

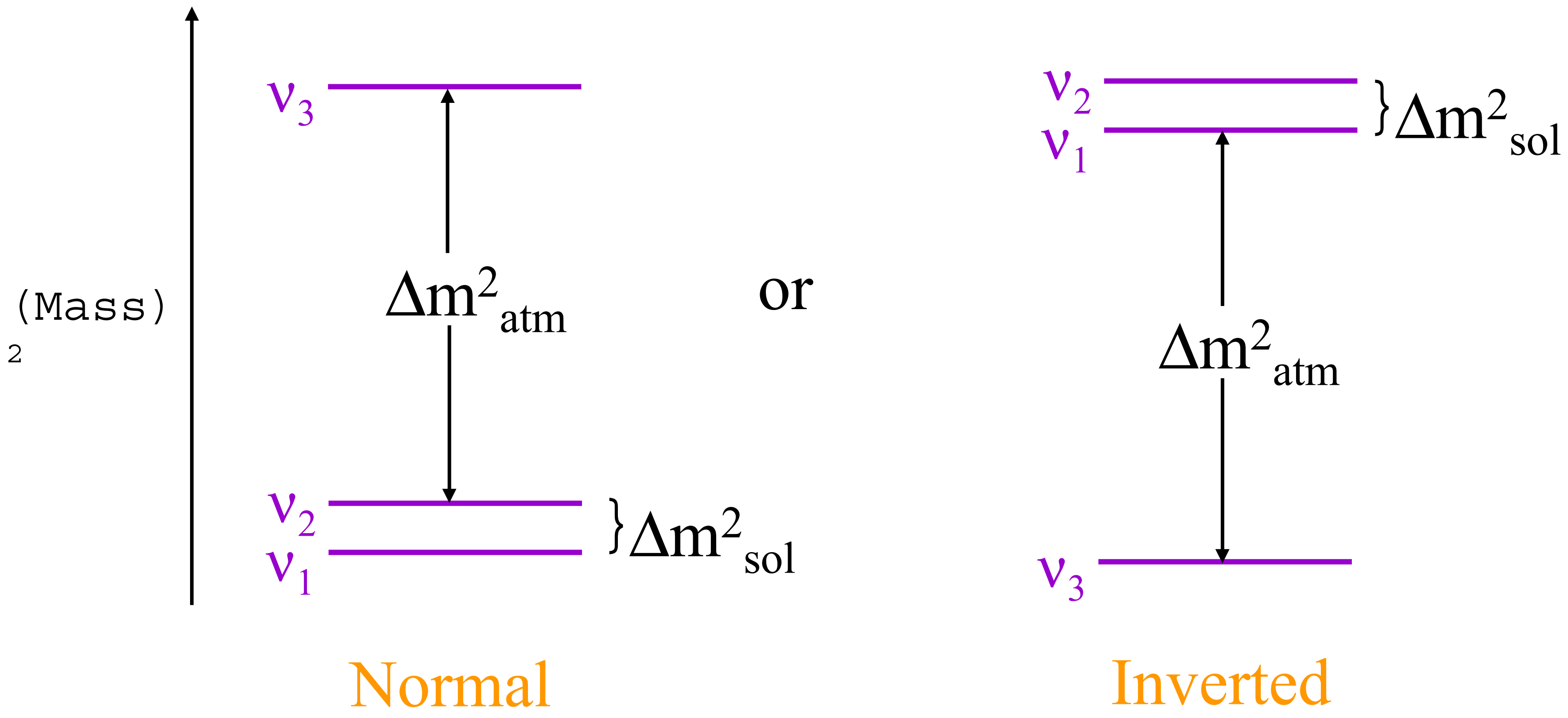
Neutrino mass & leptonic mixing

Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Compelling
Atmospheric	Compelling
Accelerator (L = 250 and 735 km)	Compelling
Stopped μ^+ Decay $\begin{pmatrix}\text{LSND}\\ L \approx 30\text{ m}\end{pmatrix}$	Unconfirmed

What We Have Learned

The $(\text{Mass})^2$ Spectrum



$\Delta m^2_{sol} \cong 8 \times 10^{-5}\ \text{eV}^2$, $\Delta m^2_{atm} \cong 2.7 \times 10^{-3}\ \text{eV}^2$

Are there *more* mass eigenstates, as LSND suggests?

The Mixing Matrix

Atmospheric · Cross-Mixing · Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

Majorana ~~CP~~ phases

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 10°$

δ would lead to $P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. ~~CP~~

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

The Open Questions

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TIFF (Uncompressed) decompressor
are needed to see this picture.

- What is the absolute scale of neutrino mass?

- Are neutrinos their own antiparticles?

- Are there “sterile” neutrinos?

We must be alert to surprises!

• What is the pattern of mixing among the different types of neutrinos?

What is θ_{13}?

• Is the spectrum like  or  ?

• Do neutrino – matter interactions violate CP?

Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

- What can neutrinos and the universe tell us about one another?

- Is CP violation involving neutrinos the key to understanding the matter – antimatter asymmetry of the universe?

- What physics is behind neutrino mass?

The Importance of the Questions, and How They May Be Answered

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Are Neutrinos Their Own Antiparticles?

For each *mass eigenstate* ν_i , does —

- $\bar{\nu}_i = \nu_i$ (Majorana neutrinos)

or

- $\bar{\nu}_i \neq \nu_i$ (Dirac neutrinos) ?

$e^+ \neq e^-$ since Charge(e^+) = – Charge(e^-).

But neutrinos may not carry any conserved charge-like quantum number.

A conserved Lepton Number L defined by—

$L(\nu) = L(l^-) = -L(\bar{\nu}) = -L(l^+) = 1$

may not exist.

If it does not, then nothing

To look for L nonconservation, seek —

Neutrinoless Double Beta Decay

L̸ will be small, so need a lot (e.g., 1 ton)

Observation would establish that —

- L is not conserved
- $\bar{\nu}_i = \nu_i$ (Neutrinos are Majorana particles)
- Neutrinos have ***Majorana masses***, unlike the charged leptons and quarks

Are There Sterile Neutrinos?

Rapid neutrino oscillation reported by the
L(iquid) S(cintillator) N(eutrino) D(etector) —

□ 1eV^2

in contrast to

$\Delta m^2_{atm} = 2.7 \times 10^{-3} \text{ eV}^2$

$\Delta m^2_{sol} = 8 \times 10^{-5} \text{ eV}^2$

⇒ At least **4** mass eigenstates, hence at least **4** flavors.

Measured $\Gamma(Z \rightarrow \nu\bar{\nu})$ ⇒ only **3** different *active* neutrinos.

⇒ At least **1** *sterile* neutrino.

Is the so-far unconfirmed oscillation reported by LSND genuine?

MiniBooNE aims to definitively answer this question.

The Central Role of θ_{13}

Both CP violation and our ability to tell whether the spectrum is normal or inverted depend on θ_{13}.

If $\sin^2\theta_{13} > (0.0025 - 0.0050)$, we can study both of these issues with intense but conventional accelerator ν and $\bar{\nu}$ beams, produced via $\pi^+ \to \mu^+ + \nu_\mu$ and $\pi^- \to \mu^- + \bar{\nu}_\mu$.

Determining θ_{13} is an important step.

Reactor Experiments

Looking for disappearance of reactor $\bar{\nu}_e$ while they travel L ~ 1.5 km with energy E ~ 3 MeV is the cleanest way to determine θ_{13} .

P($\bar{\nu}_e$ Disappearance) =

$$= \sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{atm}(eV^2)L(km)/E(GeV)]$$

Accelerator Experiments

Accelerator neutrino experiments can also probe θ_{13} , although now it is entwined with other parameters.

Their ***special*** capability is to probe *whether the mass spectrum is normal or inverted*, and to look for *CP violation*.

Both are done by studying $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ while the beams travel hundreds of kilometers.

The Mass Spectrum:  or  ?

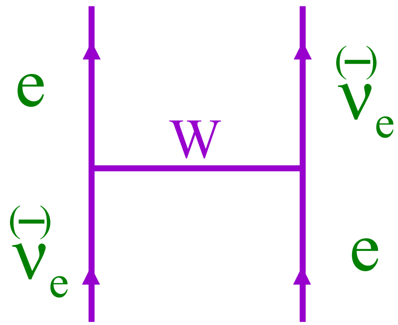
Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

 is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

How To Determine If The Spectrum Is Normal Or Inverted

Exploit the fact that, in matter,



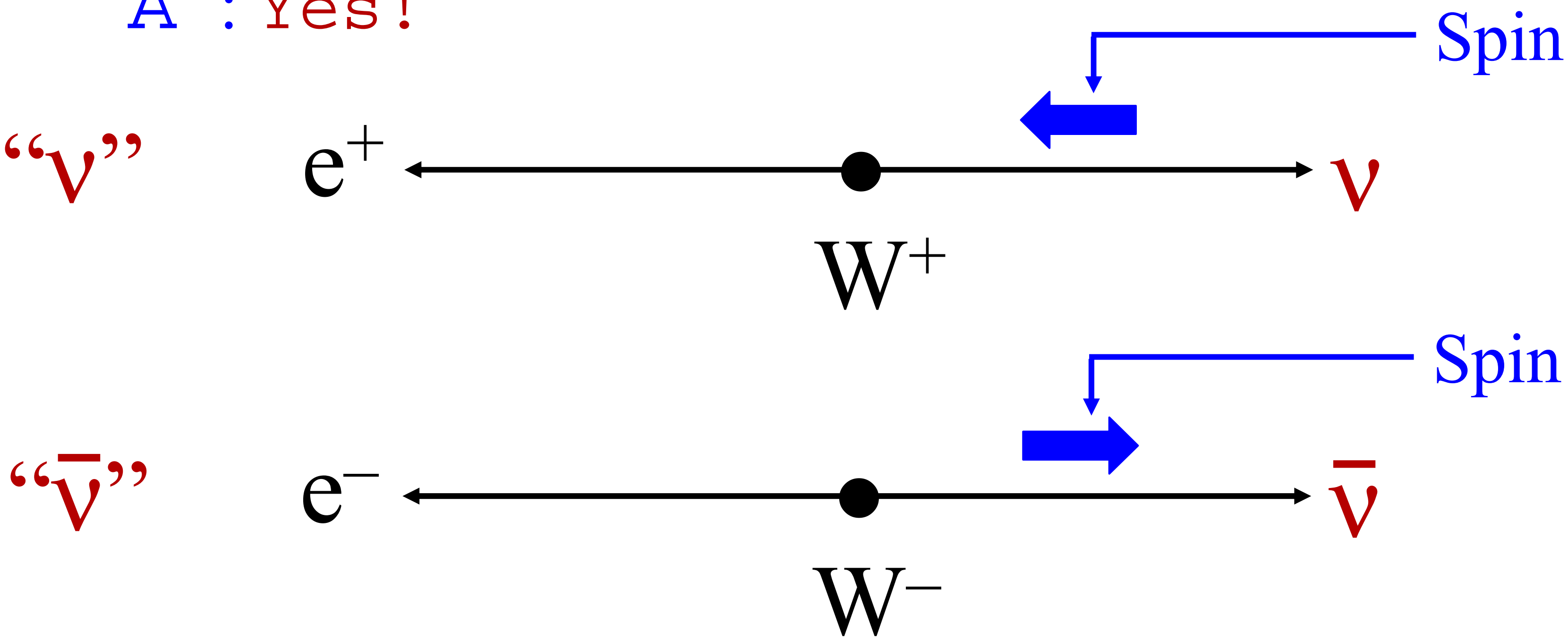
affects ν and $\bar{\nu}$ differently, and leads to —

$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} > 1\ ; \\ < 1\ ; \end{cases}$$

Note fake CP

Q : Does matter still affect ν and $\bar{\nu}$ differently when $\nu = \bar{\nu}$?

A : Yes!



The weak interactions violate ***parity***. Neutrino – matter interactions depend on the neutrino ***polarization***.

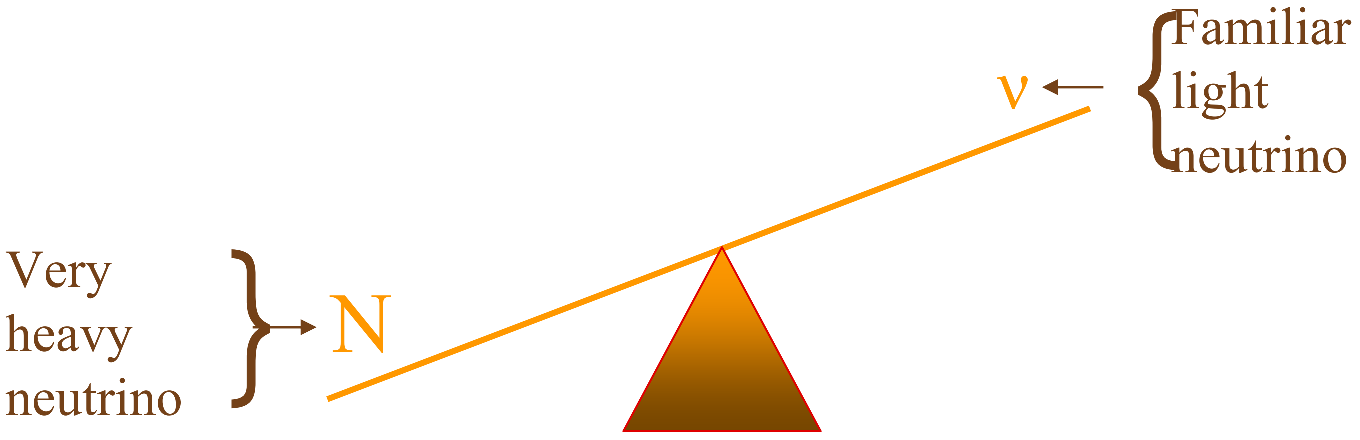
Do Neutrino Interactions Violate CP?

Is leptonic ~~CP~~, through **Leptogenesis**, the origin of the **Baryon Asymmetry** of the universe?

Leptogenesis In 60 Seconds

The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism



The heavy neutrinos N would have been made in the hot Big Bang.

The heavy neutrinos N, like the light ones ν, are Majorana particles. Thus, an N can decay into l^- or l^+.

If neutrino oscillation violates CP, then quite likely so does N decay. In the See-Saw, these two CP violations have a common origin.

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

$$N \rightarrow l^- + \ldots \qquad \text{and} \qquad N \rightarrow l^+ + \ldots$$

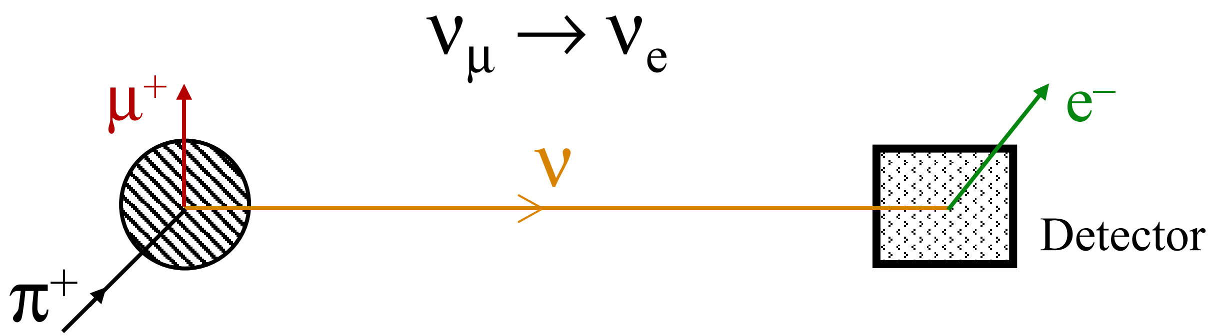
This would have led to unequal numbers of leptons and antileptons (Leptogenesis).

Then, Standard-Model ***Sphaleron*** processes would have turned ~ 1/3 of this leptonic asymmetry into a Baryon Asymmetry.

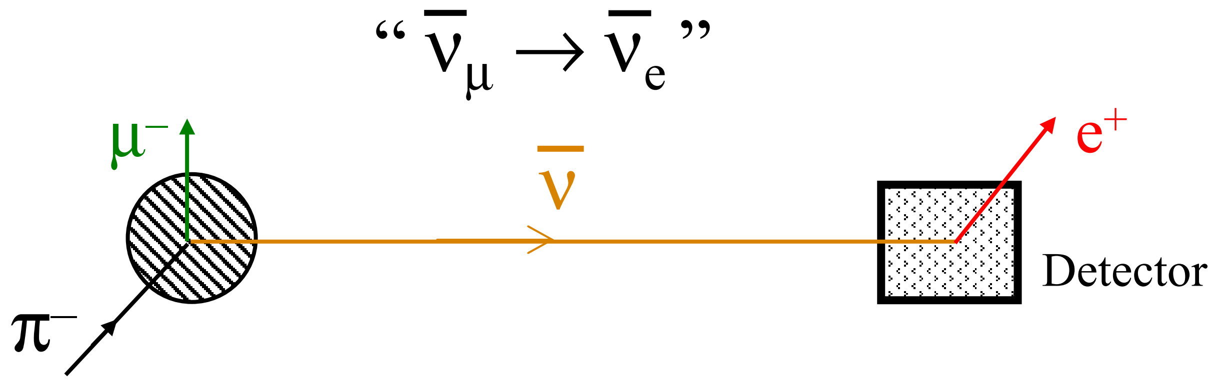
Q : Can CP violation still lead to $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq P(\nu_\mu \rightarrow \nu_e)$ when $\bar{\nu} = \nu$?

A : Certainly!

Compare



with



Separating $\not{CP}$ From the Matter Effect

Genuine $\not{CP}$ and the matter effect both lead to a difference between "ν" and "$\bar{\nu}$" oscillation.

But genuine $\not{CP}$ and the matter effect depend quite differently from each other on L and E.

To disentangle them, one must make oscillation measurements at different L and/or E.

Summary

We have learned a lot about the neutrinos in the last decade.

What we have learned raises some very interesting questions.

Strategies and experiments for answering them are being developed.