Frontiers in Neutrino Physics

- Neutrinos as a Probe
- Spectra
- Intrinsic Properties
- Astrophysics/Cosmology/Geophysics
Neutrinos as a Unique Probe: $10^{-33} - 10^{+28}$ cm

- **Particle Physics**

  - $\nu N, \mu N, e N$ scattering: existence/properties of quarks, QCD

  - Weak decays ($n \rightarrow pe^-\bar{\nu}_e, \mu^- \rightarrow e^-\nu_\mu\bar{\nu}_e$): Fermi theory, parity violation, quark mixing

  - Neutral current, $Z$-pole, atomic parity: electroweak unification, field theory, $m_t$; severe constraint on physics to TeV scale

  - Neutrino mass: constraint on TeV physics, grand unification, superstrings, extra dimensions; seesaw: $m_\nu \sim m_q^2/M_{GUT}$
• **Astrophysics/Cosmology**

- Core of Sun
- Supernova dynamics
- Atmospheric neutrinos (cosmic rays)
- Violent events (AGNs, GRBs, cosmic rays)
- Large scale structure (dark matter)
- Nucleosynthesis (big bang - small $A$; stars $\rightarrow$ iron; supernova - large $N$)
- Baryogenesis
  - **Simultaneous probes of $\nu$ and astrophysics**

• **Interior of Earth**
**Neutrino Spectra**

\( \nu \) Oscillations

- \( P_{\nu_a \to \nu_b} = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \)

3 \( \nu \) Patterns

- **Solar:** LMA
  (SNO, KamLAND, Borexino)

- \( \Delta m^2_\odot \sim 8 \times 10^{-5} \text{ eV}^2 \), mixing large but nonmaximal

- **Atmospheric + K2K + MINOS:**
  \( |\Delta m^2_{\text{Atm}}| \sim 2.4 \times 10^{-3} \text{ eV}^2 \), near-maximal mixing

- **Reactor:** \( U_{e3} \) small

http://hitoshi.berkeley.edu/neutrino

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• Mixings: let $\nu_\pm \equiv \frac{1}{\sqrt{2}} (\nu_\mu \pm \nu_\tau)$:

\[
\begin{align*}
\nu_3 & \sim \nu_+ \\
\nu_2 & \sim \cos \theta_\odot \nu_- - \sin \theta_\odot \nu_e \\
\nu_1 & \sim \sin \theta_\odot \nu_- + \cos \theta_\odot \nu_e
\end{align*}
\]

- Normal hierarchy
  - Analogous to quarks, charged leptons
  - $\beta\beta_{0\nu}$ rate very small

- Inverted hierarchy
  - $\beta\beta_{0\nu}$ if Majorana

• Degenerate pattern for $|m| \gg \sqrt{|\Delta m^2|}$
Outstanding Issues (intrinsic properties)

- **Scale of underlying physics?** (string, GUT, TeV?)
- **Mechanism?** (seesaw, LED, HDO, stringy instanton?)
- **Hierarchy, $U_{e3}$, leptonic $CP$ violation?** (mechanism, leptogenesis)
- **Absolute mass scale?** (cosmology)
- **Dirac or Majorana?** (mechanism, scale, leptogenesis)
- **Baryon asymmetry?** (leptogenesis, electroweak baryogenesis, other?)
Outstanding Issues (intrinsic properties)

- **Scale of underlying physics?**  (string, GUT, TeV?)  (LHC, flavor)
- **Mechanism?**  (seesaw, LED, HDO, stringy instanton?)  (indirect: LHC)
- **Hierarchy, $U_{e3}$, leptonic $CP$ violation?**  (mechanism, leptogenesis)  (long baseline, reactor, $\beta\beta_{0\nu}$, supernova)
- **Absolute mass scale?**  (cosmology)  ($\beta$ decay, cosmology, $\beta\beta_{0\nu}$, supernova)
- **Dirac or Majorana?**  (mechanism, scale, leptogenesis)  ($\beta\beta_{0\nu}$)
- **Baryon asymmetry?**  (leptogenesis, electroweak baryogenesis, other?)  (indirect: LHC)
Other properties

- Models
- $\nu$ interactions (MINER$\nu$A, SciBooNE, SNS [CLEAR], MicroBooNE, NuSOnG)
- Puzzles/anomalies (LSND, NuTeV, MiniBooNE, GSI)
- Quantum subtleties
- Sterile $\nu$'s (OscSNS)
- $\nu$ decay
- Electromagnetic moments
- Decoherence
- Non-standard interactions
- Neutrino counting
- Heavy $\nu$'s
- CPT, Lorentz, equivalence violation
- FCNC (associated $\bar{\nu}$, $\bar{\ell}$)
- $R_P$ violation
- $\nu \to \bar{\nu}$
- Mass-varying $\nu$'s
- Time-varying $\nu$'s
- $\nu$ interferometry
\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

- Atmospheric, \( s_{23}^2 \sim \frac{1}{2} \)
- Solar, \( s_{12}^2 \sim 0.3 \)
- Majorana only

\[ U_{e3}, \delta_{CP}, \text{hierarchy} \]

- Need \( s_{13} \neq 0 \) for leptonic CP and hierarchy by matter effects
- \( s_{13}^2 \lesssim 0.035 \) at 90% (CHOOZ reactor \( \bar{\nu}_e \) disappearance; global)

- Hints for \( s_{13} \neq 0 \): MINOS (0.7\( \sigma \) excess from \( \nu_\mu \to \nu_e \)?)

- Solar vs KamLAND

- Future reactor: near and far detectors (\( s_{13} \) only)
  - Double CHOOZ (France)
  - Daya Bay (China)
  - RENO (South Korea)
Long Baseline (LBL) Oscillation Experiments

- 3 ν oscillations, small $s_{13}$ and $\Delta m^2_{\odot}$ (Akhmedov et al, JHEP 04, 078):

$$P_{\nu_\mu \rightarrow \nu_e} = \alpha^2 \sin^2 2\theta_{12} c_{23}^2 \frac{\sin^2 A \Delta}{A^2} + 4 s_{13}^2 s_{23}^2 \frac{\sin^2 (A - 1) \Delta}{(A - 1)^2} + 2 \alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta) \frac{\sin A \Delta \sin (A - 1) \Delta}{A} \frac{\sin (A - 1) \Delta}{A - 1}$$

where

$$\alpha = \frac{\Delta m^2_{\odot}}{\Delta m^2_{\text{Atm}}} \sim 0.03, \quad \Delta = \frac{\Delta m^2_{\text{Atm}} L}{4E}, \quad A = \frac{2\sqrt{2} \text{EGF}_{\text{n}} n_e}{\Delta m^2_{\text{Atm}}}$$

- $\delta \rightarrow -\delta$ and $A \rightarrow -A$ for $P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$

- $\Delta, A > 0$ (normal), $\Delta, A < 0$ (inverted)

- In principle, determine $s_{13}, \delta, \text{hierarchy}$ (easier if $s_{13}$ from reactor)

BNL 90/50/10 (June, 2010) Paul Langacker (IAS)
<table>
<thead>
<tr>
<th>experiment</th>
<th>location</th>
<th>$L$ (km)</th>
<th>major mode</th>
<th>status</th>
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<tbody>
<tr>
<td>K2K</td>
<td>KEK–SuperK</td>
<td>250</td>
<td>$\nu_\mu$ disappear</td>
<td>completed</td>
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<tr>
<td>NUMI-MINOS</td>
<td>Fermilab–Soudan</td>
<td>735</td>
<td>$\nu_\mu, \bar{\nu}_\mu$ disappear</td>
<td>running</td>
</tr>
<tr>
<td>T2K</td>
<td>J-PARC–SuperK</td>
<td>295 O/A</td>
<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>first events</td>
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<tr>
<td>OPERA</td>
<td>CERN–Gran Sasso</td>
<td>730</td>
<td>$\nu_\mu \rightarrow \nu_\tau$</td>
<td>$\nu_\tau$ observed</td>
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<tr>
<td>NO$\nu$A</td>
<td>Fermilab–Ash River</td>
<td>810 O/A</td>
<td>$\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$</td>
<td>construction</td>
</tr>
</tbody>
</table>

BNL 90/50/10 (June, 2010)  
Paul Langacker (IAS)
Reactor + LBL: $s_{13}^2 \sim 10^{-3}$

Huber, Lindner, Schwetz, Winter, 0907.1896
NO$\nu$A and T2K

- Off-axis (narrow $E$)
- NO$\nu$A: matter effects from long baseline
- NUMI intensity upgrade (400→700 kW)
- Possible Project X beam upgrade (∼2 MW)
- Hierarchy and $\delta$ indication for favorable parameters

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Long Baseline Neutrino Experiment (LBNE)

- Fermilab to Deep Underground Science and Engineering Lab (DUSEL) (1300 km)
- 300 KT water or 100 KT LAr detector (+ p decay, $\tau \sim 10^{34-35}$ yr)
- J-PARC to Kamioka + Korea
- CERN to ? (LAGUNA study)
- Neutrino factory ($\rightarrow \mu$ collider)
- $\beta$ beams
- DAEδALUS (several stopped $\pi$ beams)

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Absolute Mass Scale

- **Tritium $\beta$ spectrum (KATRIN)**
  $$m_{\nu e} \equiv \left( \sum_i |U_{ei}|^2 m_i^2 \right)^{1/2} \to 0.2 \text{ eV}$$

- **Cosmology (WMAP7, SDDS, $H_0$)**
  $$\Sigma \equiv \sum_i m_i < 0.58 \text{ eV (95%)}$$

- **Future (Planck, ACTPol, CMBPol)**
  $$\Sigma \to 0.05 \text{ eV}$$

- $\beta\beta_{0\nu}$ observed ($m_{\beta\beta} \gtrsim 0.01 \text{ eV}$) → inverted or degenerate

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Dirac or Majorana: Neutrinoless Double $\beta$ Decay ($\beta\beta_0\nu$)

- $nn \rightarrow ppe^- e^-$ \( (m_{\beta\beta} \equiv \sum_i U_{ei}^2 m_i) \)
- **Nuclear matrix element uncertainties**
  \( (\Gamma \sim |A_{nuc} m_{\beta\beta}|^2) \)
- **Other mechanisms may dominate**
  (e.g., SUSY $R_P$)
- $\subset$ HDM: \( \tau_{1/2}(^{76}Ge) \sim 2 \times 10^{25} \text{ y} \rightarrow m_{\beta\beta} \sim (0.16 - 0.52) \text{ eV} \)
- **Cuoricino:** \( \tau_{1/2}(^{130}Te) < 3.1 \times 10^{24} \text{ y} \) (90%)
  \( \rightarrow m_{\beta\beta} < (0.19 - 0.68) \text{ eV} \) (2$\sigma$)
- **Future exps sensitive to** $\sim 0.01$-$0.02$ eV (inverted or degenerate only)

Winter, 1004.4160
Future $\beta\beta_{0\nu}$ Experiments

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{2\nu}^{1/2}$ (10$^{19}$y)</th>
<th>$T_{0\nu}^{1/2}$ (10$^{24}$y)</th>
<th>Future Experiment</th>
<th>Mass (kg)</th>
<th>Lab</th>
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<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>(4.4$^{+0.6}_{-0.5}$)</td>
<td>&gt; 0.0014[31]</td>
<td>CANDLES</td>
<td>OTO</td>
<td></td>
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<tr>
<td>$^{76}$Ge</td>
<td>(150 ± 10)</td>
<td>&gt; 19[22]</td>
<td>GERDA</td>
<td>18-40</td>
<td>LNGS</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>(9.2 ± 0.7)</td>
<td>&gt; 0.36[25]</td>
<td>SuperNEMO</td>
<td>100</td>
<td>LSM</td>
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<tr>
<td>$^{96}$Zr</td>
<td>(2.3 ± 0.2)</td>
<td>&gt; 0.0092[25]</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>(0.71 ± 0.04)</td>
<td>&gt; 1.1[25]</td>
<td>MOON</td>
<td>OTO</td>
<td></td>
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<tr>
<td>$^{116}$Cd</td>
<td>(2.8 ± 0.2)</td>
<td>&gt; 0.17[32]</td>
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<tr>
<td>$^{130}$Te</td>
<td>(68 ± 12)</td>
<td>&gt; 2.94</td>
<td>CUORE</td>
<td>204</td>
<td>LNGS</td>
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<tr>
<td>$^{136}$Xe</td>
<td>&gt; 81[33]</td>
<td>&gt; 0.12[34]</td>
<td>EXO</td>
<td>160</td>
<td>WIPP</td>
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<tr>
<td>$^{150}$Nd</td>
<td>(0.82 ± 0.09)</td>
<td>&gt; 0.0036[35]</td>
<td>SNO+</td>
<td>56</td>
<td>SNOLAB</td>
</tr>
</tbody>
</table>

Cremonesi, 1002.1437
Solar neutrinos

- \( \nu \)'s and Sun
- MSW break observed
- pep/CNO neutrinos
- Metallicity conflict (helioseismology vs optical)
- Subdominant effects (sterile, \( \mu_\nu \), interactions)
- Borexino, ICARUS, SNO+, LENA

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Supernova neutrinos

- Collapse of iron core of $M \gtrsim 8M_\odot$ star
- 99% of energy ($\gtrsim 3 \times 10^{53}$ ergs) radiated in neutrinos
- Neutronization pulse: $e^- p \rightarrow \nu_e n$ (ms)
- Bounce and expanding shock
- Neutrinosphere radiates $\nu_i + \bar{\nu}_i$ ($\sim 10$ s)
- $\bar{\nu}_e$ observed for SN1987A (Large Magellanic Cloud)
  - Confirmed picture of SN dynamics
  - Limits on $m_\nu$, $\mu_\nu$, new interactions
- Expect thousands of events for galactic SN (30-100 yr)
  - Detailed study of core-collapse supernova dynamics
  - SNEWS: The SuperNova Early Warning System
    (hours of warning and directionality)
  - Sensitive to obscured or failed supernovae
  - $\nu$ hierarchy, small $s_{13}$, mass scale
    (MSW, collective effects, time of flight)

- Keep detectors running for 50 yr!

- Experiments becoming sensitive to diffuse SN $\nu$'s from other galaxies

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass (kton)</th>
<th>Location</th>
<th>Events at 8.5 kpc</th>
<th>Live period</th>
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<tr>
<td>Baksan</td>
<td>C$<em>2$H$</em>{2n}$</td>
<td>0.33</td>
<td>Caucasus</td>
<td>50</td>
<td>1980-present</td>
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<tr>
<td>Super-K</td>
<td>H$_2$O</td>
<td>32</td>
<td>Japan</td>
<td>8000</td>
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<td>LVD</td>
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<td>1</td>
<td>Italy</td>
<td>300</td>
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<tr>
<td>KamLAND</td>
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<td>Japan</td>
<td>300</td>
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<tr>
<td>MiniBooNE</td>
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<td>0.7</td>
<td>USA</td>
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<tr>
<td>Borexino</td>
<td>C$<em>2$H$</em>{2n}$</td>
<td>0.3</td>
<td>Italy</td>
<td>100</td>
<td>2005-present</td>
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<tr>
<td>IceCube</td>
<td>Long string</td>
<td>0.4/PMT</td>
<td>South Pole</td>
<td>N/A</td>
<td>2007-present</td>
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<tr>
<td>SNO+</td>
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<td>0.8</td>
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<tr>
<td>HALO</td>
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<td>Canada</td>
<td>80</td>
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</tr>
<tr>
<td>Icarus</td>
<td>Ar</td>
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<td>NOvA</td>
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<td>Near future</td>
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<td>LBNE LAr</td>
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<td>1900</td>
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<td>LBNE WC</td>
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<td>MEMPHYS</td>
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<td>GLACIER</td>
<td>Ar</td>
<td>100</td>
<td>Europe</td>
<td>38,000</td>
<td>Future</td>
</tr>
</tbody>
</table>

Scholberg, J. Phys. Conf. Ser., 203, 012079
Neutrinos as Cosmic Rays/Secondaries

- Atmospheric neutrinos
- IceCube (+ Deep Core) and Antares
  - High energy sources (AGN, GRB)
  - Dark matter annihilation
  - $\nu$ spectrum, decay, properties
  - Ultra HE $\nu$ interactions
  - Cosmic ray composition
Geoneutrinos

- Energy output of Earth (30-45 TW) not well understood
- Radiogenic heat production: 
  \( E_{\bar{\nu}_e} < 2.6 \text{ MeV for } ^{238}U \text{ and } ^{232}Th \text{ chains} \)
- KamLAND observation
- Recent Borexino: consistent with observed (georeactor at core excluded)
- Future: SNO+, LENA
The Ultimate Challenge: Relic Neutrinos

- $\nu_i, \bar{\nu}_i$ decoupled at $\sim$ few MeV \textit{(relativistic)}
- Redshifted to \textit{form} of relativistic thermal distribution
  \[ T_\nu \sim \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.9K, \quad n_{\nu_i} \sim 50/cm^3 \]
- Indirect: BBN \textit{(} $N_\nu = 3.2 \pm 1.2$ at $z \sim 10^{10}$\textit{)}; WMAP7+SDSS+$H_0$ \textit{(} $N_\nu = 4.3 \pm 0.9$ at $z \sim 10^3$\textit{)}

- Direct detection extraordinarily difficult \textit{(22$^{th}$ century)}
  - Macroscopic forces \textit{(} $O(G_F^2)$ \textit{)} or torques \textit{(} $O(G_F)$ \textit{)}
  - $\nu$-induced $e^\pm$ emission by nuclei
  - $Z$- burst: resonant annihilation of ultra-high energy \textit{(} $10^{22-23}$ eV \textit{)}
    cosmic $\nu$ \textit{(source? flux?)}

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Conclusions

- Neutrino physics is extremely interesting
Conclusions

- Neutrino physics is extremely interesting
- Neutrino physics is extremely difficult
Neutrino Preliminaries

- Weyl fermion
  - Minimal (two-component) fermionic degree of freedom
  - $\psi_L \leftrightarrow \psi^c_R$ by CPT

- Active Neutrino (a.k.a. ordinary, doublet)
  - in $SU(2)$ doublet with charged lepton $\rightarrow$ normal weak interactions
  - $\nu_L \leftrightarrow \nu^c_R$ by CPT

- Sterile Neutrino (a.k.a. singlet, right-handed)
  - $SU(2)$ singlet; no interactions except by mixing, Higgs, or BSM
  - $N_R \leftrightarrow N^c_L$ by CPT
  - Almost always present: Are they light? Do they mix?
• Dirac Mass

- Connects distinct Weyl spinors (usually active to sterile):
  \[(m_D \bar{\nu}_L N_R + h.c.)\]
- 4 components, \(\Delta L = 0\)
- \(\Delta I = \frac{1}{2} \rightarrow\) Higgs doublet
- Why small? (Large dimensions? Higher-dimensional operators? String instantons?)
**Majorana Mass**

- Connects Weyl spinor with itself:
  \[ \frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.) \] (active);
  \[ \frac{1}{2}(m_S \bar{\nu}_L \nu_R^c + h.c.) \] (sterile)
- 2 components, \( \Delta L = \pm 2 \)
- **Active:** \( \Delta I = 1 \) (triplet or higher-dimensional operator)
- **Sterile:** \( \Delta I = 0 \) (singlet or bare mass)

**Mixed Masses**

- Majorana and Dirac mass terms
- **Seesaw** for \( m_S \gg m_D \): \( m_T \sim \frac{M_D^2}{m_S} \)
- Ordinary-sterile mixing for \( m_S \) and \( m_D \) both small and comparable