Understanding the source of electroweak symmetry breaking is the most fundamental issue in high energy physics for the coming decade.

The LHC seems assured of discovering new phenomena related to EWSB but will leave critical questions unanswered.

A 500 GeV e^+e^- linear collider can make precision measurements that discover the nature of EWSB and point the way toward higher energy phenomena. There is likely to be a need for evolution of the collider.

The e^+ e^- linear colliders are well developed technically. It is likely that we will need to make decisions on proceeding with a linear collider within the next few years. It is imperative that we understand the physics case as clearly as possible.
There are two fundamental questions before experimental high energy physics at present:

- **What is the origin of the symmetry breaking observed in the electroweak interaction?**
  - What gives the W/Z (and fermions) their mass?
  - Is there unification of forces, and if so, at what scale? Can gravity be incorporated?
  - Are there new phenomena or new particles associated with the physics responsible for EWSB?

- **What is the origin of flavors?**
  - Why three generations and the peculiar fermion mass patterns?
  - Why is there CP violation, and why is it insufficient to give the matter/antimatter asymmetry in the universe?
  - Is there some common origin for fermion masses and Yukawa couplings?
How will we make progress on these questions?

There is considerable room for intuition on how we will make progress over the next decade or so -- and these lead to different strategies for shaping the long term program.

It seems clear to most of us that some evidence for EWSB, mass generation and unification will come in the next round of experiments at LEP2/Tevatron and particularly LHC. I believe that these experiments will not tell us all we want to know -- fundamental questions will remain.

Progress can be made through study of very rare processes or precise measurements (rare K decays, g-2 etc.). These may tell us something is out there, but not what. It is preferable to go to the scale of the new phenomena if possible.

Further experiments to study flavor are highly interesting and topical -- CKM measurements for quarks, rare K decays, neutrino masses and mixings (and even ν CP violation) -- but it seems a long shot to imagine that these are going to give fundamental insights on the basic question of the origin of flavor in the near future.

Exploring the EWSB mechanism is possible with near term experiments; we should pursue these opportunities vigorously.

(the lamp post illuminates the terrain where the clues should be !)
There are two main themes for the Linear Collider physics program:

Experiments in the past decade (LEP, SLC, Tevatron, $\nu\nu$ scattering) have made precision measurements that clearly indicate the need for something like the Higgs boson.

**Study the `Higgs boson' (or its surrogate) and measure its characteristics.**

The SM Higgs mechanism is unstable; vacuum polarization contributions from the known particles should drive its mass to the force unification scale. We expect some new physics entering at the TeV scale.

**Find and explore this new physics sector.**
International effort to develop the physics case:

Work in Europe (DESY - TESLA); Japan (KEK - JLC) and North America (SLAC/LLNL/LBNL/FNAL - NLC) to develop the physics justification for the regional proposal -- but with strong international cooperation and ties through working committee chaired by Charles Baltay (US), David Miller (Europe) & Sachio Komamiya (Japan).

European studies have advanced considerably in the past year as part of the TESLA design report.

**U.S. effort**

- Slowed by Lehman review in 5/99 and cost estimate.
- Work in past year to understand the LHC case in better detail, and to reformulate the linear collider physics case for an initial step at 500 GeV (Workshop on Mar. 29 - 31 at LBL)
- Request by Peter Rosen to HEPAP: revise the 1998 Gilman subpanel report on the path to major new facilities, and steps toward formulating a plan for the US HEP community.
- Plan to produce a documented physics case (and example detectors) to accompany the NLC design report -- draft by late in this year.
What is the Higgs?

(The Higgs is what the measurements tell us it is!)

- **Higgs self-coupling diverges**
- **Λ** is the scale for new physics to appear, to avoid SM Higgs inconsistencies

(SM) $M_{\text{higgs}} < 190$ GeV at 90% CL.
LEP2 limit $M_{\text{higgs}} > 108$ (will reach 115?)
Tevatron can discover up to 180 GeV

EW higher order corrections are essential from precision measurements

$W$ mass ($\pm 45$ MeV) and top mass ($\pm 5$ GeV) agree with precision measures and indicate low SM Higgs mass
Precision studies constrain ANY any new physics generating the Higgs mechanism.

(SU(2) x U(1)  S=T = 0)

\[ \sin^2 \theta_W \]

The constraints on S & T (independent self-energy corrections) are now very tight. Any theory extending the SM must obey these.

There is nearly a `no-lose' theorem -- no matter how the SM is extended, there should be a Higgs surrogate, or some other new phenomena in the range \( M < 500 \) GeV. The theorem is not foolproof however.
Minimal Supersymmetric Model -- example of modified Higgs sector

2 complex Higgs doublets $\phi_1$ and $\phi_2$: after mass generation for $W, Z$ get:

- $h^0, H^0$ (CP even; $m_h < m_H$)
- $A^0$ (CP odd)
- $H^\pm$

If Susy mass scale is $< 1$ TeV, the lighter $h^0$ mass is below 130 GeV. The current measurements are consistent with Susy -- but no experimental observation exists.

Higgs sector in MSSM controlled by two parameters: $\tan \beta = \langle \phi_1 \rangle / \langle \phi_2 \rangle$ and $m_A$

As $m_A \to \infty$, $h^0$ becomes SM-like and $H^0, A^0, H$ become massive and nearly degenerate. (decoupling limit)

$h$ (or $H$) couplings are modified from the SM as function of $m_A$ and $\tan \beta$
Program for Higgs Study

- Find a Higgs boson candidate, and measure its mass (or masses of added Higgs states in SM extensions)
  - LHC (or LEP/Tevatron) should discover, and measure the mass adequately (unless Higgs decays dominantly to invisible modes - then the LC finds it).

- Measure its total width, and branching fractions (couplings) to all fermion pairs and gauge bosons. Are the couplings proportional to mass? Do they conform to the simple SM, or to Susy models? Do the couplings saturate the full EWSB needs (are there more Higgs?)
  - LHC will not do (or do poorly) $\Gamma_{\text{TOT}}$. Ratios of some couplings only to ~20%. Linear Collider can measure $\Gamma$ and couplings to ~5%; these are the crucial measurements for establishing the nature of the higgs.

- Measure the quantum numbers of the Higgs states: for the SM, expect $J^{P} = 0^{+}$; for Susy, both $0^{+}$ and $0^{-}$.
  - LHC will not do; Linear Collider will do well

- Explore the Higgs potential. The self-couplings lead to multiple Higgs production.
  - LHC will not do; LC can do, with sufficient luminosity

LHC should discover the Higgs state; LC should discover what it really is.
We know that the mechanism for the origin of mass must closely approximate the SM! Extensions to the SM must obey the precision constraints and seem highly likely to produce new physics at <500 GeV. The key discovery question for LC is **What is the nature of the `higgs'?** -- revealed by its quantum no’s, couplings, total width. The LHC is unlikely to do these.

LC can produce Higgs in association with Z allowing study of its decays without bias -- even invisible decays of Higgs are possible using the recoil Z.

Higgs production via ZH or WW fusion is copious. In the case of MSSM, there will be a need to raise energy to produce the heavier Higgs states.
Higgs Total Width

Measuring the lightest Higgs coupling tests whether there are any additional higher mass Higgs.

In MSSM, \( \sum_i g_{(h ZZ)i}^2 = (M_Z g_{EW} / \cos \theta_W)^2 \)

\( \Gamma_{TOT} \) gives a measure of \( M_H, \tan\beta \) (and stop mixing).

Measure BR: \( \Gamma(H \rightarrow \gamma\gamma) / \Gamma_{TOT} \) and \( \sigma(\gamma\gamma \rightarrow H) \sim \Gamma(H \rightarrow \gamma\gamma) \)

\( \Gamma_{TOT} \) (~15%) (requires \( \gamma\gamma \) operation)

OR: Use \( H \rightarrow WW^* \):

\( \text{BR}(H \rightarrow WW^*) = \Gamma_{WW} / \Gamma_{TOT} \)

\( \Gamma_{WW} \) from \( \sigma_{ZH} \) or WW fusion

Few % measurement of \( \Gamma_{TOT} \) for mass < 150 GeV. If \( \Gamma_{TOT} \neq \Gamma_{SM} \), have evidence for new physics.
Measurement of BR’s is powerful indicator of new physics (e.g. in minimal supersymmetry, these differ from the SM in a characteristic way). Higgs BR must agree with MSSM parameters from many other measurements.

We need to determine experimentally that Higgs couplings are indeed proportional to mass.

1000 fb\(^{-1}\) for 500 GeV LC

<table>
<thead>
<tr>
<th>Higgs Coupling</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H bb</td>
<td>2.4%</td>
</tr>
<tr>
<td>H cc</td>
<td>8.3%</td>
</tr>
<tr>
<td>H gg</td>
<td>5.5%</td>
</tr>
<tr>
<td>H ττ</td>
<td>6.0%</td>
</tr>
<tr>
<td>H WW</td>
<td>5.4%</td>
</tr>
</tbody>
</table>

\(\delta \text{BR/BR} \) 
\((M_h = 120 \text{ GeV})\)
Physics beyond the Standard Model

The defects of the SM are widely known:

- No gauge interaction unification occurs
- Higgs mass is unstable to loop corrections

Many possible new theories proposed to cure these ills and embed the SM in a larger framework

→ **Supersymmetry** -- fermion/boson partners, extending the Poincare group to include spin.

Supersymmetry models come in many variants with different mechanisms and scales of Supersymmetry breaking (supergravity, gauge mediation, anomaly mediation ...). Each has a different spectrum of particles, underlying parameters.

→ **A new gauge interaction** like QCD with `mesons' at larger masses. (Techicolor/topcolor) These interactions avoid introducing a fundamental scalar. `technipions' play the role of Higgs; new particles to be observed, and modifications to WW scattering.

→ **String models with some extra dimensions** compactified at millimeter -- femtometer scales. These yield anomalous photon production, heavy Z/W states. A particular type of Supersymmetry should exist.

→ LC must be able to sort out which is at work, and make precision measurements

Each such model has its own characteristic modification to the precision EW variables (S&T); running at the Z pole may be needed to refine these measurements.
Supersymmetry

Fermion/boson symmetry stabilizes the Higgs mass -- scale of new Susy particles is $O(1 \text{ TeV})$. Lightest higgs state $< 130 \text{ GeV}$.

The main issue is to measure the underlying model parameters and deduce the character of the supersymmetry and the energy scale for supersymmetry breaking.

This can be done through measurement of the masses, quantum numbers, branching ratios -- and in particular the pattern of mixing of states with similar quantum numbers -- the two stops, sbottoms, staus, and the two chargino and four neutralino states (partners of the $\gamma/Z/W$ and supersymmetric Higgs states).

The LHC should discover Susy if it exists. But disentangling the information on the full mass spectrum and particle quantum no’s/couplings and the mixings will be difficult at LHC.

The LC can make these crucial measurements, benefiting from --

- Polarization of electron beam
- Known partonic cm energy
- Known initial state ($J^P = 1^-$)
Supersymmetry studies at the Linear Collider

An example: production of selectron pairs -- have two diagrams; typically the t-channel dominates and allows measurement of neutralino couplings to lepton/slepton.

$e^+ e^- \rightarrow \tilde{e} \tilde{e}^+ \tilde{e}^- e^+ e^- e^+ e^+ e^- e^- \gamma, Z \chi^0_1$

Upper & lower edges of decay electron energy distribution from $\tilde{e}_{L,R} \rightarrow e^+ \chi^0_1$ gives masses of left and right handed selectrons.

Angular distribution of decay electrons, using both polarization states of beam $e^-$, tell us about quantum numbers, coupling of exchanged neutralino and give information on neutralino mixing, hence the underlying Susy mass parameters.

Similar studies for neutralino, chargino, stau etc. production lead to independent measures of similar parameters and enable constrained fit to Susy model.
The Linear Collider can determine the Susy model, and make progress to understand the higher energy supersymmetry breaking scale. To do this, one would like to see the full spectrum of sleptons, gaugino/higgsino states.

### Thresholds for selected sparticle pair productions -- at LHC mSUGRA model points.

<table>
<thead>
<tr>
<th>reaction</th>
<th>Point 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_1^0\chi_1^0$</td>
<td>336</td>
<td>336</td>
<td>90</td>
<td>160</td>
<td>244</td>
<td>92</td>
</tr>
<tr>
<td>$\chi_1^0\chi_2^0$</td>
<td>494</td>
<td>489</td>
<td>142</td>
<td>228</td>
<td>355</td>
<td>233</td>
</tr>
<tr>
<td>$\chi_1^+\chi_1^-$</td>
<td>650</td>
<td>642</td>
<td>192</td>
<td>294</td>
<td>464</td>
<td>304</td>
</tr>
<tr>
<td>$\chi_1^+\chi_2^-$</td>
<td>1089</td>
<td>858</td>
<td>368</td>
<td>462</td>
<td>750</td>
<td>459</td>
</tr>
<tr>
<td>$\tilde{e}\tilde{e}/\tilde{\mu}\tilde{\mu}$</td>
<td>920</td>
<td>922</td>
<td>422</td>
<td>1620</td>
<td>396</td>
<td>470</td>
</tr>
<tr>
<td>$\tilde{\tau}\tilde{\tau}$</td>
<td>860</td>
<td>850</td>
<td>412</td>
<td>1594</td>
<td>314</td>
<td>264</td>
</tr>
<tr>
<td>$Z h$</td>
<td>186</td>
<td>207</td>
<td>160</td>
<td>203</td>
<td>184</td>
<td>203</td>
</tr>
<tr>
<td>$Z H/A$</td>
<td>1137</td>
<td>828</td>
<td>466</td>
<td>950</td>
<td>727</td>
<td>248</td>
</tr>
<tr>
<td>$H^+ H^-$</td>
<td>2092</td>
<td>1482</td>
<td>756</td>
<td>1724</td>
<td>1276</td>
<td>364</td>
</tr>
<tr>
<td>$\tilde{q}\tilde{q}$</td>
<td>1882</td>
<td>1896</td>
<td>630</td>
<td>1828</td>
<td>1352</td>
<td>1010</td>
</tr>
</tbody>
</table>

**RED:** Accessible at 500 GeV

**GREEN:** added at 1 TeV

It is likely that, in the case that supersymmetry exists, one will want upgrades of energy to at least 1 TeV (and luminosities of $> 10^{34}$ cm$^{-2}$ s$^{-1}$).
For many, the introduction of fundamental scalar particles in high energy physics is itself unnatural. We have a theory (QCD for the strong interaction) in which (pseudoscalar) particles (pions) arise as bound states of fundamental fermions (quarks).

Analogs of SU(3) color are postulated (with $N_{TC}$ `technicolor' degrees of freedom, but with fermions at a higher mass scale to achieve EWSB. EWSB occurs via a gauge theory, with the `higgs' = technipions. Though inspired by QCD, the new model must differ quantitatively (slow evolution of coupling).

In some variants, the third generation SM quarks (top in particular) are singled out as being strongly coupled to the new sector (`topcolor'). $t\bar{t}$ condensates play the role of `higgs', based on analogy with NJL superconductivity.
**Observables in Strong coupling models:**

New `technicolor' particles (the vector and pseudoscalar mesons of the new interaction, top gluons etc.), should occur on the TeV scale. Since the longitudinal components of W/Z are primordial higgs particles, WW (ZZ) scattering is modified.

Present constraints on S&T suggest that composite Higgs state(s) should have mass < ~500 GeV.

**Seeing strong coupling effects will probably require LC energy above 500 GeV.** Better measurements of precision EW variables (S&T) at the Z pole will be very useful to indicate these classes of models.
Large Extra Dimensions

String theories represent the only known avenue for incorporating gravity and the microscopic forces. Until recently, hope for any observable effects from the compactification of extra dimensions was dim.

Recent suggestions that the extra dimensions could be compactified on scales larger than Planck lead to observable consequences for experiment. Since Susy is a key element in string theories, there are specific predictions for the nature of the observed Susy (e.g. the lightest neutralino should be higgsino-like -- measureable from neutralino mixing studies at the Linear Collider).

If the effective Planck mass is at the TeV scale, gravity would be modified at dimensions \(< \text{mm}\), and gravitons could be produced in experiments leading to single photon production (with missing \(E_T\) from gravitons). Cross sections for fermion pairs would be modified by graviton interference effects.

For compactification scale \(O(\text{TeV})\), Kaluza-Klein excitations of Z or gluon should exist at the TeV scale, and could be observed as excited states of the Z in the LHC or LC.

For compactification at the GUT scale, new states are unobservable, but the characteristic Susy pattern of these models should remain, and the unification pattern of the couplings should provide information.

If this is our world, it is likely that higher Linear Collider energies will be desired.
Although our experiments point to the Standard Model, the Linear Collider should be capable of illuminating the nature of physics beyond the SM. We believe that some manifestation of the equivalent to the Higgs mechanism should be seen at 500 GeV or less.

**Some Scenarios:**

1. **Higgs-like state < 150 GeV and evidence for Susy:**
   
   Linear Collider program is assured, exploring the Higgs and Susy spectrum and determining their detailed structure.

2. **SM-like Higgs seen but nothing else:**
   
   LC studies all aspects of this Higgs (couplings, width etc.) to compare with SM. Revisiting the Z-pole to refine the precision measurements will be very useful.

3. **No Higgs, no Susy seen:**
   
   Verify that no Higgs to invisible modes. Increase the energy to seek new strong-coupling or extra dimension physics. Return to the Z-pole. Scratch one’s head in all possible ways.

4. **Many new phenomena seen at LHC/LEP/Tevatron:**
   
   A wealth of new physics that needs untangling -- Linear Collider has a field day!
Conclusions

We are confident that the Higgs sector physics should exist in the range of a 500 GeV Linear Collider. Many crucial measurements will wait for the LC. Study of new physics beyond the SM can be done at the LC, but may well require operation at 1 -- 1.5 TeV.

Building the consensus within the U.S. HEP community for the next major accelerator still needs to be done. SLAC physicist participation will be a key ingredient. The HEPAP report, the Snowmass 2001 workshop and the NLC CDR are important efforts to secure this consensus.

Making the case for a multi-billion dollar project in Government will be hard! Framing the physics case in understandable terms is a critical need (in addition to cost reductions for the collider).

Bringing about an international consensus on how to proceed -- which proposal to pursue, how to site it, how to fund it -- will need all the wisdom that Lab Directors, DOE/NSF staff, and members of the HEP community can muster!