Session 6: Density Functionals
Building a Universal Nuclear Energy Density Functional (UNEDF)

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The Nuclear Landscape (adapted from Richter @INPC2004)

- **Density Functional Theory** $A > 100$
- **Coupled Cluster, Shell Model** $A < 100$
- **Exact methods $A \leq 12$**
  - GFMC, NCSM
- **Lattice QCD**
- **Chiral EFT interactions** (low-energy theory of QCD)
- **QCD Lagrangian**
Overview: Nuclear DFT State of the Art

SciDAC Project: Building a UNEDF

Physics Issues

General Themes and Investment Needs
Skyrme Hartree-Fock Energy Functionals

- Skyrme energy density functional (for $N = Z$):
  \[
  E[\rho, \tau, J] = \frac{1}{2M} \tau + \frac{3}{8} t_0 \rho^2 + \frac{1}{16} t_3 \rho^{2+\alpha} + \frac{1}{16} (3t_1 + 5t_2) \rho \tau \\
  + \frac{1}{64} (9t_1 - 5t_2) (\nabla \rho)^2 - \frac{3}{4} W_0 \rho \nabla \cdot J + \frac{1}{32} (t_1 - t_2) J^2
  \]

- Where $\rho(x) = \sum_i |\phi_i(x)|^2$ and $\tau(x) = \sum_i |\nabla \phi_i(x)|^2$ (and $J$)

- Minimize $E = \int d\mathbf{x} E[\rho, \tau, J]$ by varying the (normalized) $\phi_i$'s
  \[
  \left( -\nabla \frac{1}{2M^*(\mathbf{x})} \nabla + U(\mathbf{x}) + \frac{3}{4} W_0 \nabla \rho \cdot \frac{1}{i} \nabla \times \sigma \right) \phi_i(\mathbf{x}) = \epsilon_i \phi_i(\mathbf{x}),
  \]

- $U = \frac{3}{4} t_0 \rho + (\frac{3}{16} t_1 + \frac{5}{16} t_2) \tau + \cdots$ and $\frac{1}{2M^*(\mathbf{x})} = \frac{1}{2M} + (\frac{3}{16} t_1 + \frac{5}{16} t_2) \rho$

- Iterate until $\phi_i$'s and $\epsilon_i$'s are self-consistent

- In practice: other densities, pairing is very important (HFB), projection needed, \ldots
Deformed Mass Table in One Day!

Microscopic Mass Table

M.V. Stoitsov et al., nucl-th/0406075
J. Dobaczewski et al., nucl-th/040407

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Session 6 UNEDF Review
HFB Mass Formula: \( \Delta m \sim 1\text{–}2 \text{ MeV} \)

Deviation from experiment

![Graphs showing deviation from experiment for SkP and SLy4 models](image-url)
Shell structure in normal, superheavy, and hyperheavy nuclei

$^{132}\text{Sn}$

$^{310}\text{I}_{126}$

$^{494}\text{Lv}_{186}$

Beyond Mean Field
nuclear collective dynamics

Variety of phenomena:
- symmetry breaking and quantum corrections
- LACM: fission, fusion, coexistence
- phase transitional behavior
- new kinds of deformations

Significant computational resources required:
- Generator Coordinate Method
- Projection techniques
- Imaginary time method (instanton techniques)
- QRPA and related methods
- TDHFB, ATDHF, and related methods

Challenges:
- selection of appropriate degrees of freedom
- simultaneous treatment of symmetry
- coupling to continuum in weakly bound systems
- dynamical corrections; fundamental theoretical problems.
  - rotational, vibrational, translational
  - particle number
  - isospin

M. Bender et al., PRC 69, 064303 (2004)
What are the theoretical error bars?
Overview

Overview: Nuclear DFT State of the Art

SciDAC Project: Building a UNEDF

Physics Issues

General Themes and Investment Needs
Beyond the scientific computing and computational science research embedded in the Office of Science (SC) Core Programs, SC invests in a portfolio of coordinated research efforts directed at exploiting the emerging capabilities of terascale and petascale computing. The research projects in this portfolio respond to the extraordinary difficulties of realizing sustained peak performance for those scientific applications that require terascale and petascale capabilities to accomplish their research goals. They respond also to the need for developing collaborative software environments where distributed resources and expertise are combined to address complex questions that no single institution can manage alone.
Other SciDAC Science at the Petascale Projects

- Physics (Astro): *Computational Astrophysics Consortium: Supernovae, Gamma Ray Bursts, and Nucleosynthesis*, Stan Woosley (UC/Santa Cruz) [$1.9 Million per year for five years]

- Physics (QCD): *National Computational Infrastructure for Lattice Gauge Theory*, Robert Sugar (UC/Santa Barbara) [$2.2 Million per year for five years]

- Physics (Turbulence): *Simulations of Turbulent Flows with Strong Shocks and Density Variations*, Sanjiva Lele (Stanford) [$0.8 million per year for five years]

- Physics (Petabytes): *Sustaining and Extending the Open Science Grid: Science Innovation on a PetaScale Nationwide Facility*, Miron Livny (U. Wisconsin) [$6.1 Million per year for five years]
SciDAC Project: *Building a UNEDF* Goals

- Understand nuclear properties “for element formation, for properties of stars, and for present and future energy and defense applications”
- Scope is all nuclei \((A > 12–16)\), with particular interest in reliable calculations of unstable nuclei
- Order of magnitude improvement over present capabilities \(\Rightarrow\) precision calculations
- Connected to best microscopic physics
- Maximum predictive power with well-quantified uncertainties
- Building the EDF is the heart of the project
Universal Nuclear Energy Density Functional

Inter-Nucleon NN, NNN Interactions
AV18, EFT, $V_{\text{low-k}}$

Theory of Light Nuclei
Verification: NCSM=GFMC=CC
Validation: nuclei with $A \leq 8$

Density Functional Theory
Improved functionals
remove computationally-imposed constraints
global properties of nuclei with $A > 18$

Dynamic Extensions of DFT
LACM, GCM, TDDFT, QRPA, CI, CC
Level densities

Low-energy Reactions
Hauser-Feshbach
Feshbach-Kerman-Koonin
Fission
mass and energy distributions
<table>
<thead>
<tr>
<th>Organization</th>
<th>Team Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANL</td>
<td>S. Pieper, R. Wiringa, R. Lusk, B. Norris, J. More</td>
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<tr>
<td>LLNL</td>
<td>E. Ormand, I. Thompson, J. Escher, P. Navratil</td>
</tr>
<tr>
<td>LBNL</td>
<td>E. Ng, C. Yang</td>
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<tr>
<td>LANL</td>
<td>J. Carlson, T. Kawano</td>
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<td>ORNL</td>
<td>G. Arbanas, G. Fann, W. Shelton, K. Roche</td>
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<tr>
<td>Ames NL</td>
<td>M. Sosonkina</td>
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<tr>
<td>Central Mich. U.</td>
<td>M. Horoi</td>
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<tr>
<td>Iowa State</td>
<td>J. Vary</td>
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<td>Michigan State</td>
<td>B. Brown, T. Duguet</td>
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<tr>
<td>UNC</td>
<td>J. Engel</td>
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<tr>
<td>Ohio State</td>
<td>R. Furnstahl</td>
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<tr>
<td>U. Tennessee</td>
<td>D. Dean, T. Papenbrock, W. Nazarewicz</td>
</tr>
<tr>
<td>San Diego State</td>
<td>C. Johnson</td>
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<tr>
<td>U. Washington</td>
<td>G. Bertsch, A. Bulgac</td>
</tr>
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</table>
Outline

Overview: Nuclear DFT State of the Art

SciDAC Project: Building a UNEDF

Physics Issues

General Themes and Investment Needs
Physics Issues for UNEDF

- Extending current functionals
  - New density/momentum dependences, tensor, ...
  - Insight from microscopic approaches
  - "Exotic" functionals (e.g., orbital-dependent functionals)

- Approximating and fitting the functional
  - Apply sophisticated correlation analysis
  - Gradient expansions, DME, ...
  - How should we "fine tune" a DFT functional?

- Restoration of broken symmetries
  - Translational, rotational invariance, particle number
  - Energy functional for intrinsic quantities
  - Symmetry restoration within EDF approaches

- Pairing
  - Dealing with UV divergences from pairing in finite nuclei
  - Higher-order contributions (induced interaction)
  - Number conserving functionals for pairing
Physics Issues for UNEDF (cont.)

- Long-range physics
  - pion exchange (DME and beyond)
  - dealing with long-range correlations
- Codes to solve HFB, etc. equations
- Calculating non-Kohn-Sham observables in a DFT approach
  - single-particle properties
  - excited states
- Relativistic (or covariant) DFT phenomenology
  - What about the ”Dirac sea”?  
  - Connection to microscopic description?
- How do we connect to QCD and the free NN....N interaction?
  - Benchmark against ab initio many-body calculations
  - Candidate: Chiral EFT $\Rightarrow$ RG $\Rightarrow$ low-momentum interactions
  - Develop power counting $\Rightarrow$ error estimates
Long Term Gameplan

Nuclear DFT

$V_{\text{low } k}$

NN $\cdots$ N

Chiral EFT

NN $\cdots$ N

Lattice QCD

$\rightarrow$ LEC's

Density Functional Theory $A > 100$

Coupled Cluster, Shell Model

$A < 100$

Exact methods $A \leq 12$

GFMC, NCSM

Lattice QCD

Chiral EFT interactions

(low-energy theory of QCD)

QCD

Lagrangian

Low-mom. interactions

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Session 6 UNEDF Review
Short Term Gameplan

Nuclear DFT

DME ↑

Nuclear Matter

PT+ ↑

$V_{\text{low } k}$

$\text{NN} \cdots \text{N}$

RG ↑

Chiral EFT

$\text{NN} \cdots \text{N}$

Density Functional Theory $A > 100$

Coupled Cluster, Shell Model $A < 100$

Exact methods $A \leq 12$

GFMC, NCSM

Lattice QCD

Chiral EFT interactions (low-energy theory of QCD)

QCD Lagrangian

Low-mom. interactions

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Misconceptions vs. Correct Interpretations

- DFT is a Hartree-(Fock) approximation to an effective interaction
  - DFT can accommodate all correlations in principle; in practice, approximate functionals can fall short
- Nuclear matter is nonperturbative in the potential
  - “perturbativeness” is highly cutoff dependent
- (fill in the blank) causes nuclear saturation
  - another resolution dependent inference
- Generating $V_{\text{low } k}$ loses important information
  - long-range physics is preserved
  - relevant short-range physics encoded in potential
- $V_{\text{low } k}$ is just like a G-matrix
  - important distinction: conventional G-matrix still has high-momentum matrix elements
Constructive DFT via Effective Action  [nucl-th/0212071]

- External field $\leftrightarrow$ Magnetization
- Helmholtz free energy $F[H] \leftrightarrow$ Gibbs free energy $\Gamma[M]

Legendre transform $\Rightarrow \Gamma[M] = F[H] + HM$

$H = \frac{\partial \Gamma[M]}{\partial M}$ \quad ground state \quad $\frac{\partial \Gamma[M]}{\partial M} \bigg|_{M_{gs}} = 0$
Constructive DFT via Effective Action  \[\text{[nucl-th/0212071]}\]

- **External field** $\iff$ Magnetization
- Helmholtz free energy $F[H] \iff$ Gibbs free energy $\Gamma[M]

Legendre transform $\implies \Gamma[M] = F[H] + HM$

$$H = \frac{\partial \Gamma[M]}{\partial M} \quad \text{ground state} \quad \frac{\partial \Gamma[M]}{\partial M} \bigg|_{M_{gs}} = 0$$

- Partition function with sources that adjust densities:

$$\mathcal{Z}[J] = e^{-W[J]} \sim \text{Tr} \, e^{-\beta(H + J \bar{\rho})} \quad \implies \quad \text{path integral for } W[J]$$

- Invert to find $J[\rho]$ and Legendre transform from $J$ to $\rho$:

$$\rho(x) = \frac{\delta W[J]}{\delta J(x)} \quad \implies \quad \Gamma[\rho] = W[J] - \int J \rho \quad \text{and} \quad J(x) = -\frac{\delta \Gamma[\rho]}{\delta \rho(x)}$$

$$\implies \Gamma[\rho] \propto \text{ground-state energy, stationary at } \rho_{gs}(x)!$$
Construct $W[J]$ and then $\Gamma[\rho]$ order-by-order

- Diagrammatic \textit{expansion} (i.e., use a power counting)

\[
\text{LO : } \begin{array}{c}
\infty \quad \infty
\end{array} \\
\text{NLO : } \begin{array}{c}
\infty \quad + \quad \infty
\end{array}
\]

- Inversion method $\Rightarrow$ Split source $J = J_0 + J_1 + \ldots$
  - cf. $H = (H_0 + U) + (V - U)$ with freedom to choose $U$
  - $J_0$ chosen to get $\rho(x)$ in noninteracting (Kohn-Sham) system:

\[
\begin{array}{c}
V_{\text{trap}} \\
\end{array} \Rightarrow \begin{array}{c}
V_{\text{trap}} - J_0
\end{array}
\]
Construct $W[J]$ and then $\Gamma[\rho]$ order-by-order

- **Diagrammatic expansion** (i.e., use a power counting)

  LO : \[ \begin{array}{c}
  \hbox{Diagram}
  \end{array} \]

  NLO : \[ \begin{array}{c}
  \hbox{Correction}
  \end{array} \]

- Inversion method $\implies$ Split source $J = J_0 + J_1 + \ldots$
  - cf. $H = (H_0 + U) + (V - U)$ with freedom to choose $U$
  - $J_0$ chosen to get $\rho(x)$ in noninteracting (Kohn-Sham) system:

  Orbitals $\{\psi_i(x)\}$ in local potential $J_0(\rho, x) \implies$ propagators

  $[-\nabla^2/2m - J_0(x)]\psi_i = \varepsilon_i \psi_i \implies \rho(x) = \sum_{i=1}^{A} |\psi_i(x)|^2$

- Self-consistency from $J(x) = 0 \implies J_0(x) = \delta \Gamma_{\text{int}}[\rho]/\delta \rho(x)$
Kohn-Sham DFT and “Mean-Field” Models

KS propagators (lines) always have “mean-field” structure

\[ G_{\text{KS}}(\mathbf{x}, \mathbf{x}'; \omega) = \sum_{\alpha} \psi_{\alpha}(\mathbf{x}) \psi_{\alpha}^*(\mathbf{x}') \left[ \frac{\theta(\epsilon_{\alpha} - \epsilon_F)}{\omega - \epsilon_{\alpha} + i\eta} + \frac{\theta(\epsilon_F - \epsilon_{\alpha})}{\omega - \epsilon_{\alpha} - i\eta} \right] \]

where \( \psi_{\alpha}(\mathbf{x}) \) satisfies: \[ \left[ -\frac{\nabla^2}{2M} - J_0(\mathbf{x}) \right] \psi_{\alpha}(\mathbf{x}) = \epsilon_{\alpha} \psi_{\alpha}(\mathbf{x}) \]

- We can use the Kohn-Sham basis to calculate \( n(k) = \langle a_k^\dagger a_k \rangle \), but this is beyond standard DFT [see nucl-th/0410105]
Sources of Nonperturbative Physics for NN

1. Strong short-range repulsion ("hard core" or singular $V_{2\pi}$)
2. Iterated tensor ($S_{12}$) interaction
3. Near zero-energy bound states

However . . .
- the first two depend on the momentum cutoff
- all three are affected by Pauli blocking
- Can one improve many-body PT by lowering the cutoff?
Bethe-Brueckner-Goldstone Power Counting

Strong short-range repulsion
\[ \rightarrow \text{Sum } V \text{ ladders } \rightarrow G \]

\( V_{\text{low } k} \) momentum dependence + phase space
\[ \rightarrow \text{perturbative} \]

\[ \Lambda: \left| \mathbf{p}/2 \pm \mathbf{k} \right| > k_F \text{ and } |\mathbf{k}| < \Lambda \]

\[ F: \left| \mathbf{p}/2 \pm \mathbf{k} \right| < k_F \]
**Hole-Line Expansion Revisited** *(Bethe, Day, …)*

- Consider ratio of fourth-order diagrams to third-order:

  ![Diagram](image1)

  ![Diagram](image2)

- “Conventional” $G$ matrix has high-$k$ matrix elements
  - add a hole line $\implies$ ratio $\approx \sum_{n \leq k_F} \langle bn | (1/e)G | bn \rangle \approx \kappa \approx 0.15$
  - no new hole line $\implies$ ratio $\approx -\zeta(r = 0) \approx -1 \implies$ sum all orders

- $V_{\text{low } k}$ has no matrix elements above $\Lambda$
  - add a hole line $\implies$ still suppressed
  - no new hole line $\implies$ also suppressed (limited phase space)
  - freedom to choose single-particle $U \implies$ use for Kohn-Sham

$\implies$ **DFT via inversion method should work!**
Two-Body Correlations at Nuclear Matter Density

- Defect wf $\chi(r)$ for particular kinematics ($k = 0$, $P_{cm} = 0$)
- AV18: “Wound integral” provides expansion parameter

\[ \chi(r) = \Psi(r) - \Phi(r) \]

(\(k_F = 1.35 \text{ fm}^{-1}, k = 0\))
Two-Body Correlations at Nuclear Matter Density

- Defect \( \chi(r) \) for particular kinematics \((k = 0, P_{cm} = 0)\)
- AV18: “Wound integral” provides expansion parameter

\[ \chi(r) = \Psi(r) - \Phi(r) \]

\((k_F = 1.35 \text{ fm}^{-1}, k = 0)\)

\( ^{1}S_0 \) defect

\[ \chi(r) = \Psi(r) - \Phi(r) \]

- Argonne \( v_{18} \)
- \( \Lambda = 4.5 \text{ fm}^{-1} \)

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Two-Body Correlations at Nuclear Matter Density

- Defect wf $\chi(r)$ for particular kinematics ($k = 0, P_{cm} = 0$)
- AV18: “Wound integral” provides expansion parameter $S_0$ defect $\chi(r) = \Psi(r) - \Phi(r)$ ($k_F = 1.35 \, \text{fm}^{-1}, k = 0$)

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Two-Body Correlations at Nuclear Matter Density

- Defect wf $\chi(r)$ for particular kinematics ($k = 0, P_{\text{cm}} = 0$)
- AV18: “Wound integral” provides expansion parameter
- Extreme case here, but same pattern in general
- Tensor ($^3S_1$) $\Rightarrow$ larger defect

$^1S_0$ defect $\chi(r) = \Psi(r) - \Phi(r)$

$\left(k_F = 1.35 \text{ fm}^{-1}, k = 0\right)$

Argonne v$_{18}^{18}$
Two-Body Correlations at Nuclear Matter Density

- Defect wf $\chi(r)$ for particular kinematics ($k = 0, P_{cm} = 0$)
- AV18: “Wound integral” provides expansion parameter
- Extreme case here, but same pattern in general
- Tensor ($^3S_1$) $\Rightarrow$ larger defect
- Still a sizable wound for N$^3$LO
What are the measurable quantities?

- True observables do not change under field redefinitions or unitary transformations in low-energy effective theories
  - Examples: cross sections and conserved quantities like charge

- Many useful quantities are extracted from measurements via a convolution (e.g., using some type of factorization)
  - But these will vary with the convention used

- Conventions are renormalization prescriptions, cutoffs, ...
  - Different potentials reflect different conventions

- The convention for the long-range part of NN····N potentials is agreed to be (local) pion exchange, but differs widely for the short-range part. \((\text{Note: } V_{\text{low } k} \text{ preserves long-distance part.})\)
Quantities that vary with “convention”

→ not observables

- deuteron D-state probability
  [e.g., Friar, PRC 20 (1979)]
- off-shell effects
  [Fearing/Scherer]
- occupation numbers
  [Hammer/rjf]
- wound integrals
- short-range part of wave functions
- short-range potentials; e.g., contribution of short-range 3-body forces
Short-Term Roadmap for Microscopic Nuclear DFT

- Construct a chiral EFT to a given order ($N^3$LO at present)
- Evolve $\Lambda$ down with RG (to $\Lambda \approx 2 \text{ fm}^{-1}$ for ordinary nuclei)
  - NN interactions fully, NNN interactions approximately
- Generate density functional in effective action form
  - Hartree-Fock plus “$\approx$ second order”, use DME in $k$-space
Density Matrix Expansion Revisited [Negele/Vautherin]

- Consider an alternative to the full calculation of

\[
J_0(R) = \frac{\delta \Gamma_{\text{int}}[\rho]}{\delta \rho(R)} = \int \left( \frac{\delta \rho(R)}{\delta J_0(y)} \right)^{-1} \frac{\delta \Gamma_{\text{int}}[\rho]}{\delta J_0(y)} = - \quad \text{[Diagram]} - \quad \text{[Diagram]} + \cdots
\]

with explicit \( \rho(R), \tau(R), \ldots \) dependence

- DME: Write one-particle density matrix in Kohn-Sham basis

\[
\rho(r_1, r_2) = \sum_{\epsilon_{\alpha} \leq \epsilon_F} \psi_\alpha^\dagger(r_1) \psi_\alpha(r_2)
\]

- Change to \( R = \frac{1}{2}(r_1 + r_2) \) and \( s = r_1 - r_2 \) and resum in \( s \)

\[
\rho(R + s/2, R - s/2) = e^{s \cdot (\nabla_1 - \nabla_2)/2} \rho(r_1, r_2)|_{s=0}
\]

\[
\Rightarrow \frac{3j_1(sk)}{sk} \rho(R) + \frac{35j_3(sk)}{2sk^3} \left( \frac{1}{4} \nabla^2 \rho(R) - \tau(R) + \frac{3}{5} k^2 \rho(R) + \cdots \right)
\]
DME Compared to Skyrme Hartree-Fock

- For $N = Z$, even-even, spin-saturated nuclei
- $E[\rho, \tau] = \int d^3R \mathcal{E}(\rho, \tau)|_{\rho=\rho(R), \tau=\tau(R)}$
- Phenomenological Skyrme energy functional

$$\mathcal{E} = \frac{\tau}{2M} + \frac{3}{8} t_0 \rho^2 + \frac{1}{16} t_3 \rho^{2+\alpha} + \frac{1}{16} (3t_1 + 5t_2) \rho \tau + \frac{1}{64} (9t_1 - 5t_2) |\nabla \rho|^2 + \ldots$$

- DME energy functional

$$\mathcal{E} = \frac{\tau}{2M} + A[\rho] + B[\rho] \tau + C[\rho] |\nabla \rho|^2 + \ldots$$

- $A, B, C$ are functions of $\rho$ vs. Skyrme constants $t_i$
- Beyond a short-range expansion: long-range pion in n.m.
- Even qualitative insight is valuable!
(Nuclear) Many-Body Physics: “Old” vs. “New”

<table>
<thead>
<tr>
<th>One Hamiltonian for all problems and energy/length scales</th>
<th>Infinite # of low-energy potentials; different resolutions $\Rightarrow$ different dof’s and Hamiltonians</th>
</tr>
</thead>
<tbody>
<tr>
<td>Find the “best” potential</td>
<td>There is no best potential $\Rightarrow$ use a convenient one!</td>
</tr>
<tr>
<td>Two-body data may be sufficient; many-body forces as last resort</td>
<td>Many-body data needed and many-body forces inevitable</td>
</tr>
<tr>
<td>Avoid (hide) divergences</td>
<td>Exploit divergences (cutoff dependence as tool)</td>
</tr>
<tr>
<td>Choose diagrams by “art”</td>
<td>Power counting determines diagrams and truncation error</td>
</tr>
</tbody>
</table>
EFT and RG Make Physics Easier

- Weinberg’s Third Law of Progress in Theoretical Physics:
  “You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you’ll be sorry!”

- There’s an old vaudeville joke about a doctor and patient . . .

**Patient:** Doctor, doctor, it hurts when I do this!
**Doctor:** Then don’t do that.
Outline

Overview: Nuclear DFT State of the Art

SciDAC Project: Building a UNEDF

Physics Issues

General Themes and Investment Needs
Genral Themes

- Strive for model independence when possible (e.g., EFT approaches)
- Theoretical error bars (from systematic expansions and improved fitting techniques)
- New era of computation $\Rightarrow$ shift to using large-scale computing resources
- Exploit interdisciplinary connections
  - behavior of density functional in unitary, dilute limits (cold atoms)
  - approaches used in Coulomb DFT (e.g., ab initio DFT with optimized effective potential [OEP])
Connection to Other Session 6 Topics

- Reliable EOS extrapolation for astrophysics
  - lower densities (e.g., neutron star surface)
  - higher densities (relativity, breakdown of chiral EFT, . . .)
  - controlled extrapolation with error estimates
  - understanding 3-body forces essential

- Extend UNEDF to include Strangeness
  - Chiral EFT $\Rightarrow$ SU(3) $\Rightarrow$ few-body hypernuclei in progress
  - Follow similar path to UNEDF/EOS with strangeness?
Investment Needs

- Computational capabilities $\implies$ large-scale and coordinated
  - SciDAC project is prototype collaborative effort
  - Computer cycles AND collaboration with computer scientists
- Manpower $\implies$ need high caliber students and postdocs
- Facilities
  - How would RIA-Lite interface with SciDAC goals (and beyond)? Impact of unique measurements of masses, pairing gaps, . . .
  - Where does JLab fit in? Hypernuclear physics?