Lattice QCD and the Search for New Physics

Andreas S. Kronfeld
LQCD-ext \( \oplus \) LQCD-ARRA Review, May 10–11, 2011
Existential Questions

• What breaks electroweak symmetry?

• What generates flavor? Flavor change $V$?

• Why is $m_u < m_d$? Is $m_u = 0$ (at some scale)?

• With $\delta_{\text{KM}}$ (and $\theta$), what causes $CP$ violation?

• Without these, no chemistry or biology.
Most particle physicists expect to find the answers beyond the SM:

- experimenters searching for signals;
- theorists building models.

To recognize BSM, need precision SM.

Half the parameters are “obscured” by nonperturbative QCD: need lattice QCD.

Kuti: lattice gauge theory applied to EWSB.
Standard Model

19 Parameters

• Gauge couplings: $\alpha_s, \alpha_{\text{QED}}, \alpha_W = (m_W/v)^2/\pi$;
• Lepton masses: $m_e, m_\mu, m_\tau$;
• Quark masses: $m_u e^{i\theta}, m_d, m_s, m_c, m_b, m_t$;
• CKM: $V_{us}, V_{cb}, V_{ub}, \exp(i\delta_{\text{KM}})$;
• EWSSB: $v = 246$ GeV, $\lambda = (m_H/v)^2/2$.
• Need lattice QCD, lattice Yukawa.
SM Status

- Gauge symmetry
- Quantum numbers
- Higgs sector
- Flavor interactions

- Law of Nature
- Law of Nature
- Explore at LHC
- Test with intensity
LHC Era

- New phenomena seen at CERN’s LHC (Large Hadron Collider, 7–14 TeV pp) ⇒
  - models of new particles ⇒
  - effects on low-energy processes.

- Effects suppressed by \((\Lambda_{\text{SM}}/\Lambda_{\text{new}})^1\) or \(2\), where \(\Lambda_{\text{SM}}\) could be \(\Lambda_{\text{QCD}}, m_c, M_W, \ldots\).
Outline

• Drinks: Introduction & Data Sets
• Bread and Butter: Spectroscopy
• Appetizer: Quark Masses
• Main Course: Flavor Physics
• Dessert: Muon $g-2$
• Digestiv: Perspective
Last drink

Lattice QCD Data
### USQCD Data Mines

<table>
<thead>
<tr>
<th>what</th>
<th>who</th>
<th>MILC</th>
<th>RBC/UKQCD</th>
<th>JLab</th>
</tr>
</thead>
<tbody>
<tr>
<td>sea</td>
<td></td>
<td>staggered</td>
<td>domain-wall</td>
<td>Wilson</td>
</tr>
<tr>
<td>action</td>
<td></td>
<td>asqtad</td>
<td>HISQ</td>
<td>std</td>
</tr>
<tr>
<td>$n_f$</td>
<td></td>
<td>2+1</td>
<td>2+1</td>
<td>2+1</td>
</tr>
<tr>
<td>$a$ (fm)</td>
<td></td>
<td>0.045–0.18</td>
<td>0.045–0.15</td>
<td>0.09–0.13</td>
</tr>
<tr>
<td>$m_q$</td>
<td></td>
<td>$m_s$/10</td>
<td>$m_s$/27</td>
<td>$m_s$/5</td>
</tr>
<tr>
<td># configs</td>
<td></td>
<td>500–2000</td>
<td>100 → 1000</td>
<td>600–1800</td>
</tr>
</tbody>
</table>
Non-US Data Mines

- MILC ensembles with $n_f = 2+1$ asqtad sea most extensive anywhere.
- CP-PACS/PACS-CS and BMW ensembles $\approx$ RBC-UKQCD, but focus on masses, $f_K/f_\pi$.
- ETM $n_f = 2$ ensembles: serious SM pheno underway; also have started $n_f = 2+1+1$.
- CLS generating suite of $n_f = 2$ ensembles.
• All results presented here obtained from USQCD data mines, because:

• LQCD Projects under review today;

• non-US SM calculations lag (either $n_f \leq 2$ or not written up).

• All “USQCD” data mines generated partly outside LQCD project: NSF, pre-LQCD; RBRC, UKQCD; DOE leadership class.
Spectroscopy

Heavy-light Mesons and Quarkonium
Heavy-Light Mesons
Fermilab/MILC, Phys. Rev. D 83 (2011) 034503

• Heavy-light spin-average used to set (bare) $m_c, m_b$.

• Hyperfine splittings test.

• Historically disappointing.

• Recent Fermilab/MILC:
  \[
  \Delta_{D_s} = 145 \pm 15 \text{ MeV} \\
  \exp't \quad 143.9 \pm 0.4 \text{ MeV} \\
  \Delta_{B_s} = 40 \pm 9 \text{ MeV} \\
  \exp't \quad 41.6 \pm 1.5 \text{ MeV}
  \]
• Quarkonium spectra also provide tests.
• Broad agreement, but errors still large.

<table>
<thead>
<tr>
<th>Splitting</th>
<th>Charmonium</th>
<th>Bottomonium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This work</td>
<td>Experiment</td>
</tr>
<tr>
<td>$1P-1S$</td>
<td>$473 \pm 12^{+10}_{-0}$</td>
<td>$457.5 \pm 0.3$</td>
</tr>
<tr>
<td>$1P_1-1S$</td>
<td>$469 \pm 11^{+10}_{-0}$</td>
<td>$457.9 \pm 0.4$</td>
</tr>
<tr>
<td>$2S-1S$</td>
<td>$792 \pm 42^{+17}_{-0}$</td>
<td>$606 \pm 1$</td>
</tr>
<tr>
<td>$1^3S_1-1^1S_0$</td>
<td>$116.0 \pm 7.4^{+2.6}_{-0}$</td>
<td>$116.4 \pm 1.2$</td>
</tr>
<tr>
<td>$1P$ tensor</td>
<td>$15.0 \pm 2.3^{+0.3}_{-0}$</td>
<td>$16.25 \pm 0.07$</td>
</tr>
<tr>
<td>$1P$ spin-orbit</td>
<td>$43.3 \pm 6.6^{+1.0}_{-0}$</td>
<td>$46.61 \pm 0.09$</td>
</tr>
<tr>
<td>$1S$ $\bar{s}Q-\bar{Q}Q$</td>
<td>$1058 \pm 13^{+24}_{-0}$</td>
<td>$1084.8 \pm 0.8$</td>
</tr>
</tbody>
</table>
RBC Collaboration

- Nonperturbatively match Fermilab heavy-quark action with heavy-light.
- Test w/ bottomonium.

\[
\begin{align*}
\Delta(M) &= \text{M} \text{[GeV]} \\
\Delta\left(\chi_b^0, \chi_b^1\right) &= \text{M} \text{[GeV]} \\
\Delta(\eta_b, \Upsilon) &= \text{M} \text{[GeV]}
\end{align*}
\]

\[
\begin{align*}
a^2 [\text{fm}^2] &= 0.000 \quad 0.005 \quad 0.010 \quad 0.015 \\
\text{m_{sea}} &= 0.004 \quad 0.005 \\
\text{m_{sea}} &= 0.008 \quad 0.010
\end{align*}
\]
• $B_c$ is meson with beauty and charm.

• Mass prediction of LQCD confirmed (2005).

• Now with higher precision.
QCD Parameters
**QCD of hadrons = QCD of partons**

- Perhaps more intriguing:
  - determine $\alpha_s$ with lattice QCD;
  - discover new physics in HEP scattering.
- HEP folks still digesting this suggestion.
- February 2011 workshop.

Bethke, arXiv:0908.1135
Light Quark Masses

<table>
<thead>
<tr>
<th>Lattice QCD</th>
<th>MILC</th>
<th>RBC</th>
<th>BMW</th>
<th>HPQCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{m}_u(2\text{ MeV})$</td>
<td>1.9 ± 0.2</td>
<td>2.24 ± 0.35</td>
<td>2.15 ± 0.11</td>
<td></td>
</tr>
<tr>
<td>$\bar{m}_u(2\text{ MeV})$</td>
<td>4.6 ± 0.3</td>
<td>4.65 ± 0.35</td>
<td>4.79 ± 0.14</td>
<td></td>
</tr>
<tr>
<td>$\bar{m}_s(2\text{ MeV})$</td>
<td>88 ± 5</td>
<td>97.6 ± 6.2</td>
<td>95.5 ± 1.9</td>
<td>92.4 ± 1.5</td>
</tr>
<tr>
<td>$\bar{m}_c(\bar{m}_c)$</td>
<td></td>
<td></td>
<td></td>
<td>1273 ± 6</td>
</tr>
<tr>
<td>$\bar{m}_b(\bar{m}_b)$</td>
<td></td>
<td></td>
<td></td>
<td>4164 ± 23</td>
</tr>
<tr>
<td>when</td>
<td>2009</td>
<td>2010</td>
<td>2010</td>
<td>2009–10</td>
</tr>
</tbody>
</table>
High-Scale Puzzles

- Inequalities: \( m_t > m_b, m_c > m_s \), but \( m_u < m_d \)!
  - needed for proton to be stable.
- Light masses 4 & 9 times electron mass.
- Still nonzero: too large to solve strong CP problem \( (\Theta = \theta - \arg \det y \neq 0?!) \):
  - need axion (searched by, e.g., gammeV).
Strong CP Problem

- Quark masses arise from Yukawa couplings, $m = \nu y$ & from low-energy QCD instantons.
- CP violation $\propto \theta = \theta_{QCD} - \arg \det y < 10^{-11}$.
- If $y$ has a zero mode, then its phase can be chosen so that $\theta = 0$. No CP violation.
- Though $m_u$ small, no evidence for instanton effect big enough for a zero mode in $y$. 
Flavor Physics

Flavor Physics

• The physics of identity:
  • origin of masses and CP violation;
  • flavor-changing interactions.

• Quarks (CKM) vs. leptons (ν oscillations).

• Tight constraints on models of new physics: more lattice QCD ⇒ more tests.
Textures of Mixing

\[ V_{\text{CKM}} = \begin{pmatrix} d & s & b \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \quad u \quad \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \]

\[ U_{\text{PMNS}} = \begin{pmatrix} 1 & 2 & 3 \\ e & \mu & \tau \end{pmatrix} \]

- Patterns & their disparity not understood:
- lies beyond the Standard Model.
SM Flavor Predictions

• For numerous processes:

\[ \Gamma = \left( \begin{array}{c} \text{known factors} \\ \text{CKM factors} \end{array} \right) \left( \begin{array}{c} \text{QCD factor} \end{array} \right) \]

• Decay constants, form factors, bag factors.

• Leptonic decays, semileptonic, meson mixing.

• Same & related \textbf{QCD factors} needed BSM.
Semileptonic Decays

• Before confronting ideas new physics with flavor, must “measure” CKM.

• Semileptonic decays are usually used: compute form factor, e.g., with lattice QCD.

• Approach used for $|V_{ud}|, |V_{us}|, |V_{ub}|, |V_{cd}|, |V_{cs}|, |V_{cb}|$—all but $|V_{tq}|$.

• In SM, $|V_{tq}|$ follows because $V_{CKM}$ is unitary.
CLEO-c 818/pb

Fermilab/MILC [hep-ph/0408306]: $f_+(q^2)$

- $D^0 \rightarrow K^- e^+ \nu_e$
- $D^+ \rightarrow \overline{K}^0 e^+ \nu_e$

HPQCD [arXiv:1008.4562]: $f_+(0) = 0.747 \pm 0.019$
• New normalization (HPQCD) almost as precise as CLEO, BaBar.

• same method as for $K \rightarrow \pi l\nu$.

• Preliminary: similar advance for $D \rightarrow \pi l\nu$. 
Unitarity Triangle

• Dozens of measurements, but unitarity of CKM constrains SM predictions:

\[ V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0 \]

tracing out a triangle on complex plane.

• Results often summarized with this so-called unitarity triangle.
“tension” means the global fit prefers NP.
Decay Constants

• One of the simplest quantities is decay constant of pseudoscalar mesons, $f_\pi$, etc.

• Some results (entries in MeV):

<table>
<thead>
<tr>
<th>meson</th>
<th>MILC</th>
<th>FNAL/MILC</th>
<th>HPQCD</th>
<th>Exp’t</th>
<th>Dev ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>128 ± 3</td>
<td>—</td>
<td>132 ± 2</td>
<td>130.7 ± 0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>$K$</td>
<td>156.0 ± 0.8</td>
<td>—</td>
<td>159 ± 2</td>
<td>159.9 ± 1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>$D$</td>
<td>—</td>
<td>220 ± 9</td>
<td>213 ± 4</td>
<td>206 ± 9</td>
<td>0.1</td>
</tr>
<tr>
<td>$D_s$</td>
<td>—</td>
<td>261 ± 9</td>
<td>248.0 ± 2.5</td>
<td>257.3 ± 5.3</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Leptonic decays of $D_s$.

“Easy” and validated for $D \to l\nu$.

Was 3.8σ for $D_s \to l\nu$:

- exptl statistical σ.

Can’t blame it on charm.

Now ~1.5σ.
$B \rightarrow \tau \nu$

- HFAG (exp’t): $\text{BR} = (1.64 \pm 0.34) \times 10^{-4}$.

- With $|V_{ub}|$ and $f_B$ from lattice QCD:
  - $\text{BR} = (0.72 \pm 0.15) \times 10^{-4}$.

- Evidence for a non-Standard amplitude?
  - proposed in any extension of the standard model with a charged Higgs boson.
Exclusion Plot

- Charged Higgs: multiply BR with 
  \[1 - \tan^2 \beta \left( \frac{m_B}{m_H} \right)^2 \]^2
- Exclude part of \((\tan \beta, m_H)\) plane.
- Non-standard \(H^\pm\) overwhelms \(W^\pm\).
\[ \Rightarrow \text{hypothesis}(\Phi_{\text{SM}}, \Phi_{\text{new}}) \]

\[
\begin{align*}
B^0 & \leftrightarrow \bar{B}^0 \\
B & \rightarrow Kl^+l^- \\
B & \rightarrow \tau\nu \\
K & \rightarrow \pi\nu\bar{\nu} \\
\text{muon } g-2 & 
\end{align*}
\]

lattice QCD
Roasted Vegetables

Forecast
Future Error Budgets

• In most cases,* LQCD’s CKM errors lag those of the corresponding measurements
• and BES 3 and LHC-b will improve some!
• How will LQCD improve with continued computing (and postdoc) support?

• * except $B_s$ & $D_s$ decay constants
## Error Budget for $f_{B^0B^{1/2}}$

<table>
<thead>
<tr>
<th>Source (%)</th>
<th>HPQCD final</th>
<th>Fermilab/MILC preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics $\oplus$ chiral extrapolation</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>$\chi$PT $\oplus$ light quark discretization</td>
<td>—</td>
<td>0.4</td>
</tr>
<tr>
<td>heavy quark discretization</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$r_1^{3/2}$ (aka setting $a$)</td>
<td>2.3</td>
<td>3.0</td>
</tr>
<tr>
<td>tuning quark masses</td>
<td>1.5</td>
<td>0.6</td>
</tr>
<tr>
<td>$g_{B^*B\pi}$</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>matching</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>relativistic corrections</td>
<td>2.5</td>
<td>—</td>
</tr>
<tr>
<td>finite volume</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>6.7</strong></td>
<td><strong>6.1</strong></td>
</tr>
<tr>
<td>(Elvira Gámiz)</td>
<td>$B_s$</td>
<td>$B_d$</td>
</tr>
</tbody>
</table>
## Error Budget for $\xi$

<table>
<thead>
<tr>
<th>Source (%)</th>
<th>HPQCD</th>
<th>Fermilab/MILC</th>
<th>RBC/UKQCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics $\oplus$ chiral extrapolation</td>
<td>2.0</td>
<td>3.1</td>
<td>5–6</td>
</tr>
<tr>
<td>$\chi_{\text{PT}}$ $\oplus$ light quark discretization</td>
<td>—</td>
<td>2.8</td>
<td>7</td>
</tr>
<tr>
<td>heavy quark discretization</td>
<td>0.3</td>
<td>0.2</td>
<td>4</td>
</tr>
<tr>
<td>$r_1^{3/2}$ (aka setting $a$)</td>
<td>0.0</td>
<td>0.2</td>
<td>*</td>
</tr>
<tr>
<td>tuning quark masses</td>
<td>1.0</td>
<td>0.7</td>
<td>2</td>
</tr>
<tr>
<td>$g_{B^*B\pi}$</td>
<td>1.0</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>matching</td>
<td>0.7</td>
<td>&lt;0.5</td>
<td>2</td>
</tr>
<tr>
<td>relativistic corrections</td>
<td>0.4</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>finite volume</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>2.6</td>
<td>4.3</td>
<td>9</td>
</tr>
</tbody>
</table>
\( \xi \) in Two Years

<table>
<thead>
<tr>
<th>(Elvira Gámiz) Source (%)</th>
<th>HPQCD</th>
<th>Fermilab/MILC</th>
<th>Improvement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics ( \oplus ) chiral extrapolation</td>
<td>1.0</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>( \chi PT \oplus ) light quark discretization</td>
<td>—</td>
<td>1.6</td>
<td>2</td>
</tr>
<tr>
<td>heavy quark discretization</td>
<td>0.2</td>
<td>0.1</td>
<td>1.5</td>
</tr>
<tr>
<td>( r_f^{3/2} ) (aka setting ( a ))</td>
<td>0.0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>tuning quark masses</td>
<td>0.5</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>( g_{B^*B\pi} )</td>
<td>0.5</td>
<td>0.2</td>
<td>1.5</td>
</tr>
<tr>
<td>matching</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;1?</td>
</tr>
<tr>
<td>relativistic corrections</td>
<td>0.4</td>
<td>—</td>
<td>&lt;1?</td>
</tr>
<tr>
<td>finite volume</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>1.4</td>
<td>~2.3</td>
<td>~2</td>
</tr>
</tbody>
</table>
## Longer View

<table>
<thead>
<tr>
<th>what</th>
<th>$f_{BBB}^{1/2}$</th>
<th>$\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>now</td>
<td>6–7%</td>
<td>3–4%</td>
</tr>
<tr>
<td>two years</td>
<td>~4–5%</td>
<td>~1.5–2%</td>
</tr>
<tr>
<td>five years</td>
<td>~2%</td>
<td>~1%</td>
</tr>
</tbody>
</table>

(Claude Bernard)

These are ambitious, but worthy goals, requiring CPU, GPU and HPU. And yet Tevatron (LHC) reach is 0.4% (0.05%) for $\xi$. 

Monday, May 9, 2011
Muon $g-2$
Muon, with Spin

• (Semiclassical) Dirac theory says the muon (or electron) magnetic moment should be

\[ \mu = g \frac{e}{2m} S, \quad g_{\text{Dirac}} = 2 \]

• Quantum mechanics makes \( g - 2 \neq 0 \), from photon cloud and any sort of stuff inside it (W & Z, hadrons, nonStandard particles).
Status of $a_\mu = (g-2)/2$

Andreas Höcker, arXiv:1012.0055

<table>
<thead>
<tr>
<th>how</th>
<th>$10^{11} a_\mu$</th>
<th>$10^{11} \times \text{error}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E821 \mu^+$</td>
<td>116 592 03–</td>
<td>90</td>
</tr>
<tr>
<td>$E821 \mu^-$</td>
<td>116 592 14–</td>
<td>90</td>
</tr>
<tr>
<td>$E821 \mu^{\pm}$</td>
<td>116 592 080</td>
<td>63</td>
</tr>
<tr>
<td>$SM(\tau)$</td>
<td>116 591 894</td>
<td>54</td>
</tr>
<tr>
<td>$SM(e^+e^-)$</td>
<td>116 591 802</td>
<td>49</td>
</tr>
<tr>
<td>$HVP \ (lo)$</td>
<td>6 923</td>
<td>42</td>
</tr>
<tr>
<td>$HL \times L$</td>
<td>105</td>
<td>26</td>
</tr>
</tbody>
</table>

| $E989 \mu^+$ | 116 59–          | 16                           |

HMNT 07 (e$^+e^-$-based)
$-285 \pm 51$

JN 09 (e$^+e^-$)
$-299 \pm 65$

Davier et al. 09/1 (τ-based)
$-157 \pm 52$

Davier et al. 09/1 (e$^+e^-$)
$-312 \pm 51$

Davier et al. 09/2 (e$^+e^-$ w/ BABAR)
$-255 \pm 49$

HLMNT 10 (e$^+e^-$ w/ BABAR)
$-259 \pm 48$

DHMZ 10 (τ newest)
$-195 \pm 54$

DHMZ 10 (e$^+e^-$ newest)
$-287 \pm 49$

BNL-E821 (world average)
$0 \pm 63$

Monday, May 9, 2011
Error Budgets

error $\propto$ perimeter; area $\propto$ weight in sum in quadrature

BNL E821 $\rightarrow$ FNAL E989

Standard Model Calculation
• Only lattice QCD can reduce the theoretical uncertainty to match E989.

• HVP bibliography (omitting conference proceedings subsumed into publications):
  • C. Aubin and T. Blum, Phys. Rev. D 75, 114502 (2007) [hep-lat/0608011].
• **HLxL bibliography:**

• **USQCD projects proposed for 2011-2012:**
  - Christopher Aubin (PI): Hadronic contributions to the muon $g–2$ using Asqtad staggered fermions
  - Taku Izubuchi (PI): ... Hadronic contributions to the muon anomalous magnetic moment
  - Saul Cohen (PI): Radiative decays of neutral mesons
Outlook

• Lattice QCD shaping HEP’s perspective on $\alpha_s$, quark masses, and flavor physics:
  • in some cases with no alternative.

• Still, however, at the beginning: LQCD precision lags experiment on $f_\pi, f_K$, meson mixing, and semileptonic form factors.
• At the outset of the LQCD Project, the USQCD Collaboration forecast the reduction in errors with LQCD resources.

• **A Case Study of the Impact of Increased Computational Resources on Lattice Gauge Theory Calculation: Constraints on Standard Model Parameters**

• Key results \((B_K, f_{BBB}^{1/2}, \xi, |V_{cb}| & |V_{ub}|)\) shown here have all met these aspirations.
Experiments involved:


- Charm: BES-3, FOCUS, CLEO-c, Belle, BaBar.

- $B$: LHC-b, ATLAS, CMS; BaBar, Belle, CLEO, CDF, D0.

• Science groups within the LQCD Project (USQCD collaboration) are the world leaders in flavor physics.

• Muon $g - 2$ is a new challenge: unacceptable not to rise to it.
Questions?