Instrumentation Development Laboratory: An Introduction

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For the gang
June 2003
Why are we here?

People have long asked,

"What is the world made of?"

and

"What holds it together?"
Why are we here?

What is the World Made of?

Why do so many things in this world share the same characteristics?

People have come to realize that the matter of the world is made from a few fundamental building blocks of nature.

The word "fundamental" is key here. By fundamental building blocks we mean objects that are simple and structureless -- not made of anything smaller.

Even in ancient times, people sought to organize the world around them into fundamental elements, such as earth, air, fire, and water.
Today we know that there is something more fundamental than earth, water, air, and fire...

By convention there is color,
By convention sweetness,
By convention bitterness,
**But in reality there are atoms and space.**

- Democritus (c. 400 BCE)

Around 1900, people thought of atoms as permeable balls with bits of electric charge bouncing around inside.

**But is the atom fundamental?**
Why are we here?

Is the Atom Fundamental?

People soon realized that they could categorize atoms into groups that shared similar chemical properties (as in the Periodic Table of the Elements). This indicated that atoms were made up of simpler building blocks, and that it was these simpler building blocks in different combinations that determined which atoms had which chemical properties.

Moreover, experiments which "looked" into an atom using particle probes indicated that atoms had structure and were not just squishy balls. These experiments helped scientists determine that atoms have a tiny but dense, positive nucleus and a cloud of negative electrons (e⁻).

Trivia: The term "atom" is a misnomer. Why?
Why are we here?

Is the Nucleus Fundamental?

Because it appeared small, solid, and dense, scientists originally thought that the nucleus was fundamental. Later, they discovered that it was made of protons ($p^+$), which are positively charged, and neutrons ($n$), which have no charge.

So, then, are protons and neutrons fundamental?
Why are we here?

What is Fundamental? Are Protons and Neutrons Fundamental?

Physicists have discovered that protons and neutrons are composed of even smaller particles called quarks.

As far as we know, quarks are like points in geometry. They're not made up of anything else.

After extensively testing this theory, scientists now suspect that quarks and the electron (and a few other things we'll see in a minute) are fundamental.
Why are we here?

What is Fundamental? The Modern Atom Model

This is the modern atom model.

Electrons are in constant motion around the nucleus, protons and neutrons jiggle within the nucleus, and quarks jiggle within the protons and neutrons.

This picture is quite distorted. If we drew the atom to scale and made protons and neutrons a centimeter in diameter, then the electrons and quarks would be less than the diameter of a hair and the entire atom's diameter would be greater than the length of thirty football fields! 99.9999999999% of an atom's volume is just empty space!

We are essentially nothing!
Why are we here?

Scale of the atom.

While an atom is tiny, the nucleus is ten thousand times smaller than the atom and the quarks and electrons are at least ten thousand times smaller than that. We don’t know exactly how small quarks and electrons are; they are definitely smaller than $10^{-18}$ meters, and they might literally be points, but we do not know.

It is also possible that quarks and electrons are not fundamental after all, and will turn out to be made up of other, more fundamental particles. (Oh, will this madness ever end?)
Why are we here?

Physicists have developed a theory called **The Standard Model** that explains what the world is and what holds it together. It is a simple and comprehensive theory that explains all the hundreds of particles and complex interactions with only:

- **6 quarks.**
- **6 leptons.** The best-known lepton is the electron. We will talk about leptons in just a few pages.
- **Force carrier particles**, like the photon. We will talk about these particles later.

All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles.

The Standard Model is a good **theory**. Experiments have verified its predictions to incredible precision, and all the particles predicted by this theory have been found. But it does not explain everything. For example, gravity is not included in the Standard Model.
Why are we here?

What is the World Made of?  Quarks

Quarks are one type of matter particle. Most of the matter we see around us is made from protons and neutrons, which are composed of quarks.

There are six quarks, but physicists usually talk about them in terms of three pairs: up/down, charm/strange, and top/bottom. (Also, for each of these quarks, there is a corresponding antiquark.) Be glad that quarks have such silly names -- it makes them easier to remember!

Quarks have the unusual characteristic of having a fractional electric charge, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called color charge, which we will discuss later.

The most elusive quark, the top quark, was discovered in 1995 after its existence had been theorized for 20 years.
Like social elephants, quarks only exist in groups with other quarks and are never found alone. Composite particles made of quarks are called hadrons. 

**Hadrons**

...are any hadron which is made of three quarks (qqq).

Because they are made of two up quarks and one down quark (uud), **protons** are baryons. So are **neutrons** (udd).

**Baryons**

...contain one quark (q) and one antiquark ($\bar{q}$).

One example of a meson is a pion ($\pi^+$), which is made of an up quark and a down antiquark. The antiparticle of a meson just has its quark and antiquark switched, so an antipion ($\pi^-$) is made up a down quark and an up antiquark.

Because a meson consists of a particle and an antiparticle, it is very unstable. The kaon ($K$) meson lives much longer than most mesons, which is why it was called "strange" and gave this name to the strange quark, one of its components.

**Mesons**

A weird thing about hadrons is that only a very very very small part of the mass of a hadron is due to the quarks in it.
Why are we here?

The other type of matter particles are the leptons.

There are six leptons, three of which have electrical charge and three of which do not. They appear to be point-like particles without internal structure. The best known lepton is the electron (e⁻). The other two charged leptons are the muon (νμ) and the tau (ντ), which are charged like electrons but have a lot more mass. The other leptons are the three types of neutrinos (ν). They have no electrical charge, very little mass, and they are very hard to find.

Quarks are sociable and only exist in composite particles with other quarks, whereas leptons are solitary particles. Think of the charged leptons as independent cats with associated neutrino fleas, which are very hard to see.

For each lepton there is a corresponding antimatter antilepton. Note that the anti-electron has a special name, the "positron."

Trivia: "Lepton" comes from the Greek for "small mass," but this is a misnomer. Why?
What is the World Made of?  The Generations of Matter

Note that both quarks and leptons exist in three distinct sets. Each set of quark and lepton charge types is called a generation of matter (charges +2/3, -1/3, 0, and -1 as you go down each generation). The generations are organized by increasing mass.

All visible matter in the universe is made from the first generation of matter particles -- up quarks, down quarks, and electrons. This is because all second and third generation particles are unstable and quickly decay into stable first generation particles.

Wait a minute. If the higher generations of matter decay quickly, are rarely observed, and do not make up any of the stable matter around us, why do they exist at all?

Good question. In fact, when the muon was discovered physicist I.I. Rabi asked,

So why do we have generations of matter at all? Why three of them? We don't know. And without understanding why the second and third
What Holds it Together?  The Four Interactions

Now we think we have a good idea of what the world is made of: quarks and leptons. So...

What holds it together?

The universe, which we know and love, exists because the fundamental particles interact. These interactions include attractive and repulsive forces, decay, and annihilation.

There are four fundamental interactions between particles, and all forces in the world can be attributed to these four interactions!

That's right: Any force you can think of -- friction, magnetism, gravity, nuclear decay, and so on -- is caused by one of these four fundamental interactions.

What's the difference between a force and an interaction?

This is a hard distinction to make. Strictly speaking, a force is the effect on a particle due to the presence of other particles. The interactions of a particle include all the forces that affect it, but also include decays and annihilations that the particle might go through. (We will spend the next chapter discussing these decays and annihilations in more depth.)

The reason this gets confusing is that most people, even most physicists, usually use "force" and "interaction" interchangeably,
Why are we here?

Electro-Magnetism
Strong
Weak
Why are we here?

As you have seen, everything from galaxies to mountains to molecules is made from quarks and leptons. But that is not the whole story. Quarks behave differently than leptons, and for each kind of matter particle there is a corresponding antimatter particle.
Why are we here?

What is the World Made of? Matter and Antimatter

For every type of matter particle we’ve found, there also exists a corresponding antimatter particle, or antiparticle.

Antiparticles look and behave just like their corresponding matter particles, except they have opposite charges. For instance, a proton is electrically positive whereas an antiproton is electrically negative. Gravity affects matter and antimatter the same way because gravity is not a charged property and a matter particle has the same mass as its antiparticle.

When a matter particle and antimatter particle meet, they annihilate into pure energy!

\[ E = mc^2 \]
Why are we here?

Slow down! "Antimatter?" "Pure energy?" What is this, Star Trek?

The idea of antimatter is strange, made all the stranger because the universe appears to be composed entirely of matter. Antimatter seems to go against everything you know about the universe.

But you can see evidence for antimatter in this early bubble chamber photo. The magnetic field in this chamber makes negative particles curl left and positive particles curl right. Many electron-positron pairs appear as if from nowhere, but are in fact from photons, which don't leave a trail. Positrons (anti-electrons) behave just like the electrons but curl in the opposite way because they have the opposite charge. (One such electron-positron pair is highlighted.)

If antimatter and matter are exactly equal but opposite, then why is there so much more matter in the universe than antimatter?

Well... we don't know. It is a question that keeps physicists up at night.
Why are we here?

**Unsolved Mysteries**  **Beyond The Standard Model**

The Standard Model answers many of the questions about the structure and stability of matter with its six types of quarks, six types of leptons, and four forces. But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

Why can't the Standard Model predict a particle's mass?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons?

How does gravity fit into all of this?
Why are we here?

From symmetry, must produce an equal amount of matter and anti-matter:

So why are we here?

\[ E = mc^2 \]
Main Projects

Accelerator based:
Precision Measurement

Non-accelerator:
Highest energies

Search for new physics:
Cutting-edge of exploring our universe
And everything between...
Belle Experiment at KEK

- **Tsukuba Science City**
  - About 60km from Tokyo/airport
Belle Experiment at KEK

- KEK:
  - Kou-Enerugii butsuri-gaku Kenkyuu-jyou (now even longer)
KEK-B Accelerator
Belle Experiment at KEK

- Belle isn’t an acronym:
  - Beauty in French – studying b quarks (also called bottom)
The **Belle** Collaboration

A World-Wide Activity
Involving ~50 Institutions

~300 members

SVD Group
Frankfurt
U. Hawaii
Kanagawa U.
KEK
Krakow INP
U. Melbourne
National Taiwan U.
Niigata U.
Osaka U.
Princeton U.
U. Sydney
Tohoku U.
U. Tokyo
Tokyo Inst. Tech.
Tokyo Metropolitan U.
U. Tsukuba
Vienna
Proper-time difference ($\Delta t$)

$e^-$: 8.0 GeV
$e^+$: 3.5 GeV

$\Upsilon(4S)$
$\beta \gamma \sim 0.425$

$B_{\text{tag}}$

$\Delta z \cong c \beta \gamma \tau_B \sim 200 \, \mu$m

$\Delta z = \frac{\Delta z}{c \beta \gamma}$

Flavor tag

$\Delta \Delta = \text{resolution}$
Example Event

Rare decay: $B^0 \rightarrow \pi^+\pi^-$
World’s highest Luminosity Collider!!

Integrated luminosity

Daily luminosity: still increasing!

Just exceeded 150fb⁻¹ yesterday!
Many Important Results!

- Discovery (w/BaBar) of CP-violation in the B-system
  - Expected, but large and clean
  - CP-violation in Kaon system tiny

- Recent first observation in $B \rightarrow \pi\pi$
  - Detector working well, but already starting to think of the future
  - Incremental Detector improvements
  - Seriously higher luminosity needed to probe non Standard-model effects – upgrade of accelerator and detector
Belle Mission

- Observation of CP violation in B decays
  - Achieved in 2001
- Observation of direct CP violation in B decays and other parameters of CKM matrix
  - by 2006 with the gradual improvement of KEKB
- Explore New Physics beyond the Standard Model
  - off-diagonal elements (e.g. study of SUSY breaking)
  - need much higher luminosity
TOF: Systematics Limited

Abstract

The Belle TOF system gives a time resolution of about 100 ps for high-momentum muons in dimuon events but 115 ps for pions and kaons in hadron events. This note examines various effects responsible for the poorer resolution for hadrons. Three effects are found to bias times and broaden the time resolution: tracks hitting near gaps between TOF counters, tracks with inconsistent predicted and calculated z positions, and tracks for which adjacent TOF counters have hits.

PACS numbers:

Core part \sim 100\,\text{ps}

But tails!!!

RMS \sim 150\,\text{ps}

Fig. 15: TOF resolution versus momentum for negative pions (squares) and muons (circles) in 2-photon events. The pions are from 4-pion final states in exp. 17 runs 800-937. Muons are from dimuon final states in exp. 19 runs 1000-1599. For comparison, the resolutions for pions in HadronC events from exp. 23 runs 552-609 are shown as diamonds. The resolution values are from Gaussian fits to A\chi distributions.
Why Such A Variance???

- **Intrinsic Performance:**
  - Tough to get
  - Beam tests don’t require sustained operation
  - Hadronic Calibration!
    - Very important – details omitted due to space limitations
    - Much work, no fundamental understanding
    - Velocity dependent (dE/dx?) fudge
    - Systematic, so no SQRT(2)
    - May be TWC technique dependent
  - Sad history of underperformance:
    - CLEO, CPLEAR, BESII, ...
  - Error Budget!!

- **Graph:**
  - Beam: negative 2.0 [GeV/c]
  - Time resolution [ps]
  - Z [cm]
  - 3cm\textsuperscript{t} TOF
  - 5cm\textsuperscript{t} TOF
Time Walk Correction

• Reasonable functional form
  – But as background increases...

• Many ideas: e.g. direct digitization at high speed?

Peter Grach
Limitations

DIRC + MDC

BaBar

Looks like BaBar does better.

Belle
TOP Counter

- Looks good, though Time-of-Propagation depends on photon wavelength
Cherenkov Ring folding

To measure $X$ instead of $\Phi$

The ring image can be obtained in TOP vs. $X_{\text{true}}$

$CCT$ is limit as $X \rightarrow \text{small}$

Not so different from DIRC partial ring reconstruction
Electronics – scenarios

Butterfly TOP

~5mm pos. resolution: 40 Ch/counter
*200 counters = 1440 channels
Multi-hit (hidden cost) >1440 channels

Bar TOP

~few mm x few mm: few Ch/counter
*~100 counters: few 100k channels

Focusing DIRC

~1mm pos. resolution: 200 Ch/counter
*180 counters = 36,000 channels

Instrumentation Dev. Lab Meeting – June, 2003
Time Stretcher Module

- Designed with LRS
  - R&D 100 Award

- 16 Channels/1 per DC
- Stretch factor 20x
- RF clock Reference

VIPA Standard Module
MTS1 Silicon (1)
Evaluation Board

- Quick and simple test board – Hulya to design/build and test a proper test board
MTS1 Timing Residuals

\[ \sigma \sim 49 \text{ps} \]
\[ \text{RMS} \sim 51 \text{ps} \]

- However, this value includes the (large) system jitter

Gordon - readout

Jim – NTS32
Occupancy issues

- Pixel for $R < 3\text{ cm}$
- Pipeline for $R < 10\text{ cm}$

Trigger simulation study desirable

Large ambiguity even with dedicated simulation. Need to be conservative.
Pixel Detector

• Board here (Fang working on)
• Test SNR vs. frame rate, etc.
• New board (student opportunity)
High Luminosity!

At $L = 10^{35}$ cm$^{-2}$/s:
• Pipelined readout:
  128k channels equiv., 40MHz x 2bytes

  10 Tera-bytes per second!  
  (10,000 CDs per second)

  ↓

Global Decision logic trigger: 10kHz
• FIFO: 128k channels equiv., 16 bytes

  20 Giga-bytes per second!  
  (200 GbE links)

  ← COPPER, online Farm

  ↓

  200 Mega-bytes per second!  
  (max. data rate to tape)
Common Electronics

- COPPER (CCommon Pipelined Platform for Electronics Readout)
- Card ~ crate – aid in data reduction
- On board data reduction

(Yangheng, Doug working on)
CuEval FINESSE

- Front-end INstrumentation Entity for Sub-detector Specific Electronics

- Dual 128kB RAM
- 480 Mbps USB2.0
- COPPER Interface

Hardware “ready” – Yangheng working on USB drivers
ANITA

ANITA
Antarctic Impulsive Transient Antenna

A long duration balloon mission to constrain the origin of the highest energy particles in the universe

UNIVERSITY OF HAWAII AT MANOA

UC Irvine
University of California, Irvine

Instrumentation Dev. Lab Meeting – June, 2003
The Flux Problem

• At $E > 10^{21}$...

• Life is tough

$$\int \int \int dr \, d\phi \, d\theta$$

$\theta$, $\phi$, $\theta$
Antarctic Impulsive Transient Antenna (ANITA)

- ANITA Goal: Pathfinding mission for GZK neutrinos
- NASA SR&T funded since October 2002, launch in 2006
ANITA concept

Antarctic Ice at 
f<1GHz, T<-20C :

• ~Lossless RF transmission

• Minimal scattering

• largest homogenous, RF-transmissive solid mass in the world
ANITA Payload

Simulated pulse—multiple antennas

- ANITA antennas view ~2pi sr with 60 deg overlapping beams
- Beam intensity gradiometry, interferometry, polarimetry used to determine pulse direction & thus original neutrino track orientation
STRAW2 Chip

Self-Triggered Recorder Analog Waveform (STRAW)

16 Channels of 256 deep SCA buckets

Optimized for RF input Microstrip 50Ω

Target input Bandwidth: >700MHz

Record length: 128-256ns

Die: ~2.5mm²

Self-Triggering:
- LL and HL (adj.) for each channel
- Multiplicity trigger for LL hits

On-chip ADC:
12-bit, >2MSPS

Sampling Rate:
1-3GSa/s (adj.)

Sampling Rates
>~8GSa/s possible w/ 0.25μm process

External option:
MUXed Analog out

Under Test
STRAW2 Evaluation

- Adjustable: 0.6 – 3.4 GSa/s
- 256 samples (70 – 300ns)

- RF signal input
RF Response

- Sub-ns transient ping: <= 100ps leading edge

**RF Comparison**

- Scope ET sampling: 100 Gsa/s equiv.
RF Response (2)

- **Low Power!** (250mW/16 channels = < 20mW/channel @ 3.3 GSa/s)

STRAW3 target: $f_{3dB} \sim 1.2GHz$

STRAW2 already useable for NaCl applications
ANITA-lite (prototype)

RF test flight in December – equipment to Texas in July

Jim, Mary & David assy.
Antenna testing and development

- Anechoic test chamber
- Up to 400 lb embedded salt stack
- PCB antenna development
  - Muon test chamber
  - SLAC T460
Horn Antenna Prototype

Dan Yi
Cosmic-ray Radio Testbed

Testbed goals:

- Detect first Askaryan signals of cosmic origin
  - Use (rare) multi-TeV muon or single hadron showers
  - Scintillation counter trigger provides particle tag
  - 48 channel digitization via time-multiplexing
- Development of large-scale DAQ needed for full-scale detector
  - ~200 total antenna signals present
- Operational since early August!
  - Data analysis underway

- Foreground: electronics rack & cable delay
- Background: salt chamber with amplifiers

DALI upgrade – Jim/Mary assy, Justin & Johnson readout
Natural Salt Domes: Potential PeV-EeV Neutrino Detectors

- Natural salt can be extremely low RF loss:
  - as radio clear as Antarctic ice
  - ~2.4 times as dense
- typical salt dome: 50-100 km³ water equivalent in top ~3km

Qeshm Island, Hormuz strait, Iran, 7km diameter salt dome

Isacksen salt dome, Elf Ringnes Island, Canada 8 by 5km

Caprock visible from space
GEISER

• Gigabit Ethernet Instrumentation for SalSA Electronic Readout
• David, Laine & Justin
• Prototype of real system – what better way to gain experience
  • Much better than some bogus R&D (Research and Disposal)
  • If works, may actually be deployed

http://www2.hawaii.edu/~ridley/
• With so much going on – critical to document

• Kim has done a nice start, opportunities to expand

• Plan to expand the “People” section to include bios and work experience

  • This can be a very nice pointer to work experience in your future

  • I routinely get asked for recommendations and it is useful to have something in the public domain

http://www.phys.hawaii.edu/~idlab
Cross-Training

• Lab Interaction
  – Encourage you to learn about what each other working on
  – Very useful to be able to share ideas

• Lab Basic Training
  – General Lab procedures (notebook, documentation)
  – Electronics (handling, reading schematics, parts id)
  – Soldering and hand wiring
  – Computer usage
  – Clean room (wire-bonding, materials handling)

I will be away July 17 – August 11:
If stuck on a project, good time to receive additional training and learn new tools and skills
Preview of Coming Attractions

• Ongoing projects
  – Student Opportunities!! Tell your friends
  – Success depends on you

• Other opportunities
  – Jr./Sr. research projects [GEISER interesting]
  – Directed study
  – Publications (NIM/IEEE articles for MTS1 and STRAW2)
  – Board/firmware/chip design (this summer)
  – Many designs in queue; CDF, COW, MTS2, SalSA, and pixel chips
    • Design, layout, simulation and test opportunities

Thoughts on how to improve things always welcome