Physics For The 21st Century

Unit 2: The Fundamental Interactions

Srini Rajagopalan and Ayana Arce

The Strong Nuclear Force, the Weak Nuclear Force, Electromagnetism, and Gravity: these are the four fundamental interactions underlying all known phenomena in the universe.

While physicists have identified these forces, and know much about how they work, there is still a lot to learn. Some physicists believe that other, yet to be discovered, interactions may exist.

The Large Hadron Collider, or LHC, is based at the European Organization for Nuclear Research, or CERN in Switzerland. It is the largest and most complicated scientific machine ever created. The LHC collides protons at energies and collision rates higher than any other particle accelerator ever built, generating data that will advance our knowledge of the mysterious fundamental forces that govern our universe.

> AYANA ARCE: *The LHC is really a discovery machine. It can produce basically anything that's allowed by the laws of the universe.*
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> SRINI RAJAGAPOLAN: *Physicists are excited about the LHC because we are going where no one has gone before.*

Srini Rajagopalan, a physicist at Brookhaven National Laboratory, is coordinating the effort to develop hardware and software triggers capable of filtering billions of LHC collisions, in real time, to ensure that the most interesting results are recognized and saved for later analysis.

> SR: *We have a crucial responsibility. If we make a mistake, there is no second chances, so we have to get it right.*

One of the many physicists performing analyses on the filtered data is Ayana Arce of Duke University. Arce compares the filtered LHC data with computer simulations to spot unusual events that might have been captured in the filtered data.

> AYANA ARCE: *We are trying to search for and characterize the unknown to understand the fundamental interactions of matter and energy.*

Both scientists are working as part of a collective that includes over half

the world's particle physicists, all sharing the same ultimate goal to probe deeper than ever before into the nature of the fundamental particles of the universe, and the way that they interact.

Part I: The ATLAS Trigger

Srini Rajagopalan

The Standard Model of particle physics is the best theory that physicists have to describe both elementary particles and the interactions, or forces, that influence them.

> SRINI RAJAGOPOLAN: *Everything that you see around you, whether it's you, whether it's the universe, the stars, it's made up of 12 fundamental particles. And the Standard Model describes them, and the forces that govern the strong, the weak, and the electromagnetic. It still does not accommodate the force we all know, which is gravity.*

Each of these three forces, or interactions, is associated with a particle or set of particles, which allow that interaction to take place. So the particles and the interactions in the standard model cannot be thought of as separate, mutually exclusive entities, but are intertwined.

While the Standard Model has significantly advanced our understanding of the universe and is one of the greatest scientific achievements, it is still incomplete.

> SR: *The biggest question is, "What generates the mass of these particles"? Some particles weigh less, some weigh more - why?*
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> *But there are other things, for example, when the universe was born there must have been equal amounts of matter and antimatter, and it should have annihilated. So we shouldn't exist. Which means that somehow there was some excess amount of matter over antimatter. Why?*

Physicists believe that one explanation for these and other gaps in the Standard Model could be the existence of particles or interactions still to be discovered. And because particles and interactions are so intimately related, the discovery of one would affect our understanding of the other.

New particles can be created as energy is converted into mass in high-energy collisions. Collisions at very high energies could create heavy particles that have never been seen before. And a high collision rate

increases the chance of observing a rare event, which is what is done in the largest particle collider in the world–the Large Hadron Collider, or LHC.

> SR: *There's a lot of new physics that the LHC can explore. And that's what we'll be doing.*

The LHC accelerates beams of protons in counter-rotating directions reaching energies of up to 7 Trillion Electron Volts, or 7 TeV, approximately ten times more energetic than its closest rival: Fermilab's Tevatron Collider.

When two protons collide, they create particles that immediately start to decay into more particles that in turn can decay into still lighter particles. Particle decay proceeds through the fundamental interactions.

On the relative rare occasion that two protons collide, any particle with a mass smaller than the collision energy can be created. Higher energy collisions produce heavier particles, which decay into less energetic, lighter particles.

> SR: *The LHC will be able to explore higher mass ranges because it is operating at* higher *energy scales, and because energy and mass are related.*
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> *It allows us to look for particles like the Higgs or other particles that could exist, but was beyond the reach of previous generation accelerators.*

In the hunt to discover new physics, six detectors are situated along the LHC, each associated with a different project, each aiming to extend our understanding of matter and forces. The largest is the: A Toroidal LHC ApparatuS, or ATLAS detector. It weighs approximately 7,000 tons, is over 5 stories tall, and located 100 meters below earth's surface.

> SR: *Here we are in the ATLAS control room. ATLAS has 2,800 collaborators from 35 or so countries, so there are many, many physics analysts. People are going through the data trying to extract the physics either to look for new physics or to make precision measurements.*

The LHC is not just operating at unprecedented energy levels, but will also have an unprecedented luminosity, the measure used to express the number of collisions of protons per second. More collisions per second produce more data, which must be captured, analyzed, and preserved for later analysis.

SR: *If you put more protons in a bunch, okay, and you have two proton bunches colliding into each other, and you have more and more protons in each bunch, then the probability that you have multiple interactions is higher.*

Srini Rajagopalan is coordinating the trigger activities in ATLAS. He leads a large team of physicists, engineers and software professionals responsible for the Trigger, the hardware and the software that selects and records data in real time coming from the ATLAS detector.

SR: *I've taken on many roles in ATLAS, but for the past couple of years I have been working on the trigger. Our role is to ensure that the trigger works. It includes the development of algorithms, making sure that the algorithms execute efficiently. Our role is to make sure that we can analyze events rapidly every second so that we can explore the undiscovered physics and we can make precision measurements. We have a crucial responsibility. If we make a mistake, there is no second chances, so we have to get it right.*

What physicists are looking for in data recorded from the detector is evidence that new particles or interactions may have been present.

Collisions generate massive amounts of raw data that describe every aspect of every collision. Most of these data represent events that can be understood using well-established physics. It is believed, however, that some of these events will not be easily understood. These interactions, known as "candidate events," may hold the key to the missing pieces of the Standard Model.

Enabling the ATLAS detector to identify and record these critically important candidate events is no easy task.

SR: *ATLAS is like a camera, which means it is like taking 40 million pictures every second and ATLAS has to look at it and select interesting events and write them out to disk. We write out events to disk at about 200 Hz, which means we accept 200 of these 40 million pictures every second.*

To filter 200 events from 40 million every second is the job of the Trigger. It involves a three step filtering process, the level one trigger, the level two trigger and the event filter, each level conducting a finer analysis than the previous.

SR: *The Level-1 has to look at the 40 million pictures, see which ones are interesting, and select about 75 thousand pictures. That is now given to this Level-2. The Level-2 gives about 2,000 of those* *pictures to the event filter. The event filter then takes those and writes out about 200 of those pictures.*

The Level-1 trigger has two and a half millionths of a second to decide whether to send an event to the next level. The detectors used to make this decision are the electromagnetic calorimeter and the muon spectrometer.

Calorimeters can be thought of as thermometers, but instead of measuring temperature, they measure the energy deposited by particles produced in a collision. The electromagnetic calorimeter is specifically designed to measure the energy of particles that interact via the electromagnetic force: electrons and photons.

HOWARD GORDON: *Okay this is a mockup of the ATLAS liquid argon electromagnetic calorimeter for the barrel.*

Howard Gordon is the U.S. ATLAS Deputy Operations Program Manager at Brookhaven National Laboratory. This laboratory was responsible for the design and construction of part of the ATLAS electromagnetic calorimeters.

HG: *These boxes are these boxes here. That yellow area is what we see over here in the mockup in true size. Some of the things that we expect will occur in the Large Hadron Collider in the ATLAS experiment are the production of photons and electrons. And a photon or an electron has a particular signature in this calorimeter. It would have localized electromagnetic energy. By localized, I mean it'll just be in a region of maybe this - this wide. All the energy will be here, and the energy would be sampled by these electrodes. So when the energy in a given region exceeds a certain threshold that triggers a pulse, which is the Level-1 trigger.*

It is not just the electromagnetic calorimeter that determines if an event is interesting. Other components, such as the hadronic calorimeter and the muon spectrometer, send different data about the event that also require almost instantaneous analysis.

David Francis, a physicist at CERN, is co-leader of the Trigger and Data Acquisition systems in ATLAS and responsible for the operation of these electronics housed 100 meters below the earth.

DAVID FRANCIS: *So the signals arrive on these fiber optics, these orange fiber optics, where they're analyzed by custom-built electronics, electronics specifically designed for the ATLAS detector. Various features of the data are looked for. If yes, something interesting happened, from the Level-1 point of view, the* *data associated to that specific proton-proton collision is then analyzed by the other two levels of the ATLAS trigger.*

SR: *The Level-2 is a software algorithm that accesses the data, but it accesses data only in a region of interest, which means that it doesn't look at the entire detected data. It looks at the data around the region where the Level-1 thought it saw something good. And it looks at that and it says, "Is it good? Is it true? Is it?" And it does a finer analysis.*

The final analysis is made by the event filter, where multiple aspects of the event are put together and it is comprehensively analyzed. Each event is advanced to the next level only if it meets the trigger's specific criteria. Scientists looking for specific types of events order triggers using a multi-tiered menu system.

SR: *We can set up many, many triggers. We have a thousand triggers looking at different types of signatures.*

If I was setting up a trigger for the electron, what I would look for is an energy deposition in the electromagnetic calorimeter, and a track in the tracking chamber. If I was looking for a muon, I would look for hits in the muon chamber, and a possible track in the tracking chamber.

The particles in the detector are the by-products of the decay of heavier particles. So when we learn about how a particle decays, we learn about the interaction by which it decays.

SR: *If somebody is looking at an undiscovered physics, then they would have a model on how that physics happens. What are the end decay products? What should we be looking at in the detector? And then we understand that. We translate that into what the triggers should be that can capture that physics, should it happen.*

After events of interest have been sifted and the data has been recorded, it is distributed to a multi-tiered grid of computer centers around the globe for further processing and backup. The filtered data is then, again, distributed around the globe and made available for physicists to study.

Andreas Hirstius is one of the network engineers responsible for distributing these data.

ANDREAS HIRSTIUS: *The lines you see coming in and out represent data flowing in or out, or jobs flowing in or out of CERN and the results returning to CERN. So we have, at the moment,* *about 65,000 jobs running around the world. And the data transfer rate is about two gigabytes a second.*

Once the data has been filtered down to a handful of interesting events, it can be reconstructed into a workable form for physicists to analyze.

SRINI RAJAGOPALAN: *This is an event recorded by ATLAS at a center of mass energy of 2.36 TeV. You can see the interaction point, where the protons collided. You can see tracks in the inner detector systems, extrapolated to the vertex point. You can see energy deposition in the electromagnetic calorimeter, which is shown in gray, the hadronic calorimeter, which is shown in red. And you can, perhaps, see some hits in the muon chambers, which are outside.*

Data from collision events like these still require further reconstruction to be useful for detailed investigation.

When processed and verified they will potentially lead to the discovery of new physics about the fundamental interactions and the Standard Model.

Part II: ATLAS Data Analysis

Ayana Arce

Scientists all over the globe receive the data for analysis. But how can physicists be sure that data recorded by the detector is accurate and useful for further study?

One of the many physicists performing verification of ATLAS data is Ayana Arce of Duke University. Arce compares the filtered ATLAS data with computer simulations to spot unusual events that might have been captured in this data.

AYANA ARCE: *In our research we are trying to search for and characterize the unknown. We are trying to produce new kinds of particles and interactions and study these interactions to put together a clearer picture of how the universe works at its most fundamental level.*

To find answers, to understand physics beyond the Standard Model, what we're trying to do with the detector is take a snapshot of the aftermath of collisions of protons, and from that snapshot to look backwards and try to figure out what the fundamental interaction underlying that event was.

To achieve this, Arce runs computer simulations that replicate as closely as possible these particle collisions.

> AA: *We can't understand the nature of interactions by only looking at one event. That's impossible because the laws of physics don't tell us what happened in a specific event. The laws of physics tell us the relative probabilities of different things taking place in a proton-proton collision.*
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> *So, in order to quantify what we think might have happened, what we often do is simulate particle collisions and their interaction with the detector and compare a lot of simulated events to a lot of recorded events. And if this comparison matches up, then we think we understand not only what our detector was doing, but also what took place in that initial collision.*

Arce's simulations use the Monte Carlo technique. This method, named for the city famous for its casino games, is analogous to rolling dice over and over again to figure out the probability of every possible combination. But in this case, instead of rolling dice they are simulating particle collisions.

> AA: *The Monte Carlo uses random number generators in the computer to decide what particles will be produced and what angles they will move towards, and what energies they will have, and how their subsequent interactions will take place, because these processes are inherently random. And since they're random, we can only learn from them by studying a large number of similar interactions. And the Monte Carlo allows us to generate large numbers of simulated interactions, which we can study to our hearts' content before we look at the real data.*
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> *Now if you see a rare event, something that you don't understand, what you'll do is go back to your Monte Carlo where you've plugged in all of the physics that you already know. You've plugged in the Standard Model. And you'll take that Monte Carlo and analyze it with an identical set of software tools to reconstruct events, and then you'll compare the Monte Carlo to the events that you've seen. If that rare, that weird event is still there, and it's never generated by your Monte Carlo but you've seen it many times in data, then it's a signal that there's something new that you don't understand.*

Developing software that simulates particle interactions is a difficult task. To add to its complexity, physicists must also simulate the interactions of the particles with the detector.

> AA: *The easiest thing to simulate is an ideal detector that takes perhaps zero lines of code because the input to the detector simulation is a description of what went into the collision, what happened during the collision, and everything that came out, all of the particles that came out, their energies, their momenta, where they went. If we had an ideal detector, that's exactly what the detector would tell us. Since it's not a perfect detector, it sometimes misidentifies particles. It might see a pion and say it's an electron. And because it's not a perfect detector in terms of resolution, it might misreport the energy off by three or four percent. So, a perfect detector is no simulation at all. The imperfect detector takes a very careful understanding of the limitations of the technology that we've built.*

But how can physicists be sure that the detector is working correctly?

When the LHC first came online, it operated at reduced energy levels, generating events that were predictable, based on collisions previously observed in smaller colliders. Arce can use data from well-understood events as a calibration tool.

She is currently looking at top events, events that produce the top quark.

> AA: *The top quark is the heaviest matter particle that we know about. I'm specifically looking for the events where a pair of top quarks, or specifically a top quark, and its antimatter partner, the anti-top, are both produced in the same collision. And this is the most likely way to get top quarks at the LHC.*
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> *So we've generated top events, meaning we've used a program that acts as the LHC collider will to create simulated interactions that result in top quarks, and then to decay those top quarks, and to decay the particles that the top quarks decayed into. And we've done this millions of times.*

When a top quark is produced, either in simulation or in reality, it immediately decays into lighter particles, which decay into even lighter particles as they fly through the detector. Some of these particles deposit energy into the detector, and others pass through leaving no trace. Physicists must act as detectives, using the clues left in the detector to infer what actually happened in the initial collision and the full set of particles that appeared in the aftermath.

To detect top quarks, or any other massive particle produced within the ATLAS detector, it is necessary to create triggers that recognize signals from specific decay products.

When a top quark decays, the most likely result is a W boson and a bottom quark. These particles also decay quickly, so the trigger must recognize the products later on in the decay chain. The easiest signature to detect is when the W decays into either a muon, tau, or electron and its associated neutrino. These particles are called leptons.

> AA: *Top quarks can produce leptons, and those leptons can be produced with a range of energies. The trigger will set a lower limit, or a threshold on the energy of the leptons that it accepts. One of the things I'm checking is whether the trigger threshold is low enough that I accept a large fraction of the top quark events that are produced.*
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> *And taking these millions of top quark events, I am now running through the simulated detector data, calculating quantities based on that detector data, the same way I would for the real data. And I am going to look at the results of the selected events to see how much I can learn from them.*

Simulated top events are not only useful for calibration purposes, but studying the top quark could help reveal useful information about the Standard Model and the existence of the elusive Higgs Boson, believed to be the only particle within the Standard Model not yet observed.

> AA: *I've always been looking at the top quark. And the reason is basically because the top quark is the heaviest matter particle that we know about. And because it's very massive, it has a special interaction with the Higgs. The Higgs would like to interact with the top quark more than it would like to interact with an electron. That's why the top quark is so much heavier than an electron. But the fact that we don't understand exactly how the Higgs gives mass to particles, we don't exactly understand the Higgs' own mass -- we haven't even measured that yet -- tells us that maybe there's something more to this story.*

The work of writing and testing simulation and verification software is one shared with thousands of other physicists around the globe.

> AA: *When you ask who's responsible for the software, the short answer is that we all are because we all use all of the aspects of the software. We have all seen times when it needs to be improved, and we've all basically contributed those improvements.*
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> *Once all of those little tunings and tweakings are done and we have a detector simulation that describes events we understand very well*

the same way as the data, then we can start to look at events that we don't understand in the data. We can look in new corners of phase space, new kinds of interactions. And since we trust now the detector simulation, then by comparing that simulation to those interactions, we can see if a kind of physics that we already know about is taking place or if it's something new.

Ayana Arce's work in conjunction and collaboration with physicists like Srini Rajagopalan and thousands of others around the world is being conducted with the same goal in mind: to create the most sensitive and most effective tool possible with hopes of revealing new physics and new relationships between the fundamental interactions.

SRINI RAJAGOPALAN: *There must be new physics out there and LHC should see the new physics.*

AYANA ARCE: *There's a theory that takes the strong nuclear force and unifies it with the weak and the electromagnetic force, If all of these forces come from one sort of fundamental property, it would simplify our description of the physical universe.*

But only more measurements of new properties of these new particles or new interactions are going to let us know that this hypothetical model is actually the right one