National Aeronautics and Space Administration

NASA

Issue #7

ASTROBIOLOGY

The Story of our Search for Life in the Universe

Produced by the NASA Astrobiology Program to commemorate 50 years of Exobiology and Astrobiology at NASA.

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Astrobiology

A History of Exobiology and Astrobiology at NASA

This is the story of life in the Universe—or at least the story as we know it so far. As scientists, we strive to understand the environment in which we live and how life relates to this environment. As astrobiologists, we study an environment that includes not just the Earth, but the entire Universe in which we live.

The year 2010 marked 50 years of Exobiology and Astrobiology research at the National Aeronautics and Space Administration (NASA). To celebrate, the Astrobiology Program commissioned this graphic history. It tells the story of some of the most important people and events that have shaped the science of Exobiology and Astrobiology. At only 50 years old, this field is relatively young. However, as you will see, the questions that astrobiologists are trying to answer are as old as humankind.

Concept & Story

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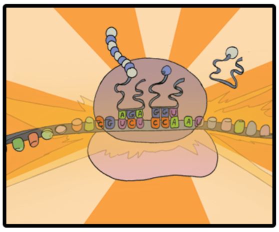
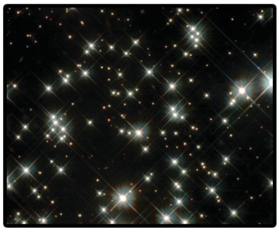
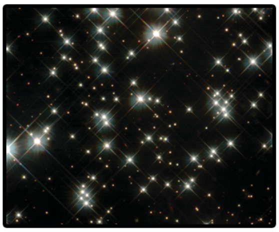
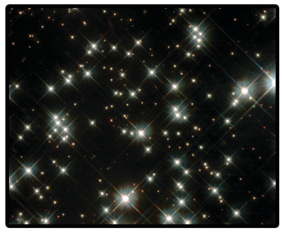
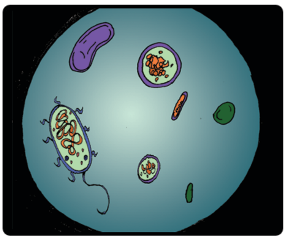
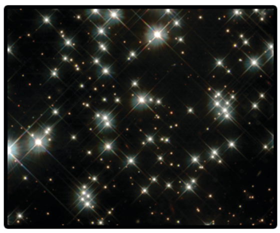
Issue #7—Prebiotic Chemistry and the Origin of Life

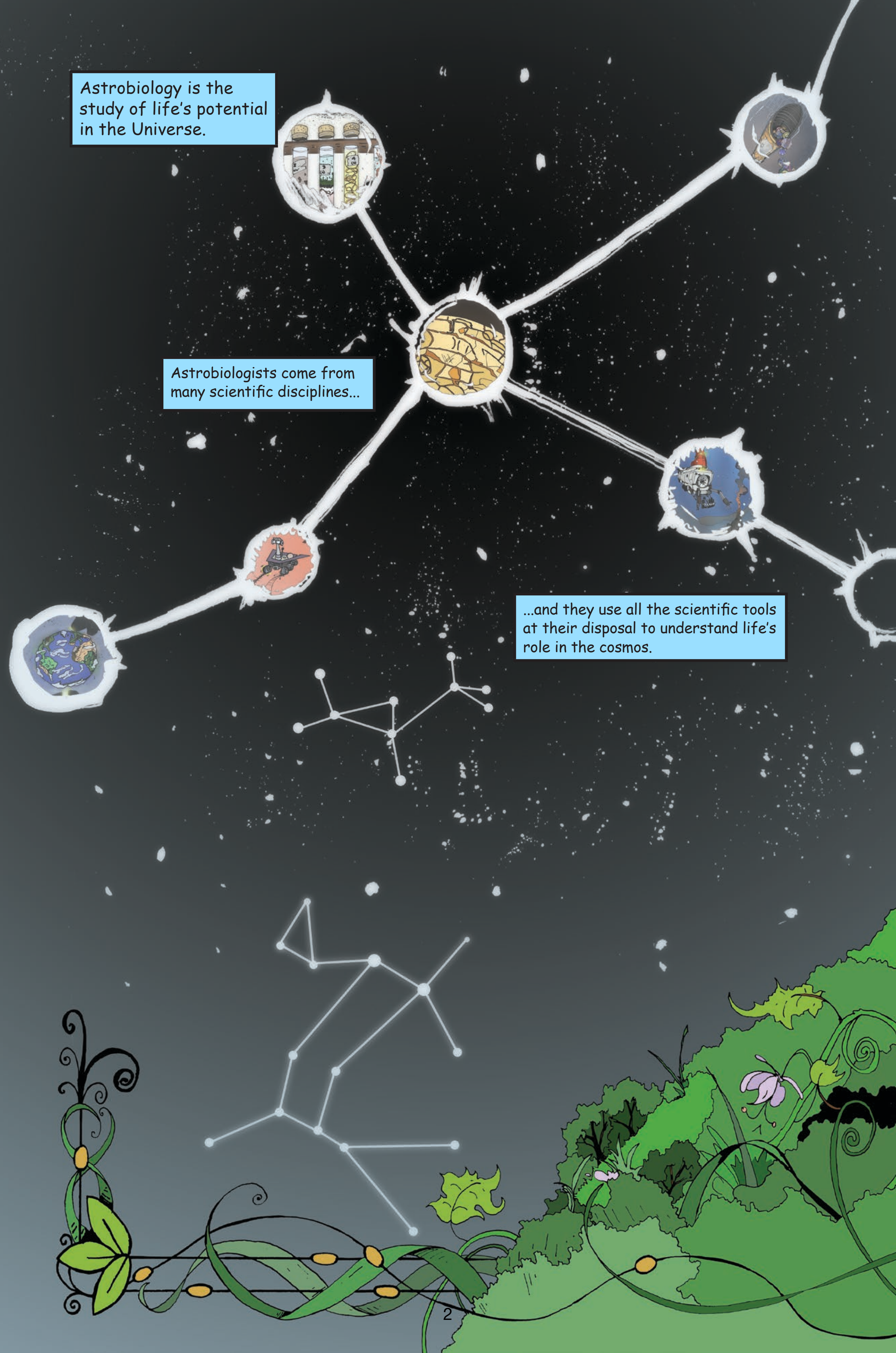






The year 2010 marked the 50th anniversary of NASA's Exobiology Program, established in 1960 and expanded into a broader Astrobiology Program in the 1990s. To commemorate the past half century of research, we are telling the story of how this field developed and how the search for life elsewhere became a key component of NASA's science strategy for exploring space. This issue is the seventh in what we intend to be a series of graphic history books. Though not comprehensive, the series has been conceived to highlight key moments and key people in the field as it explains how Astrobiology came to be.

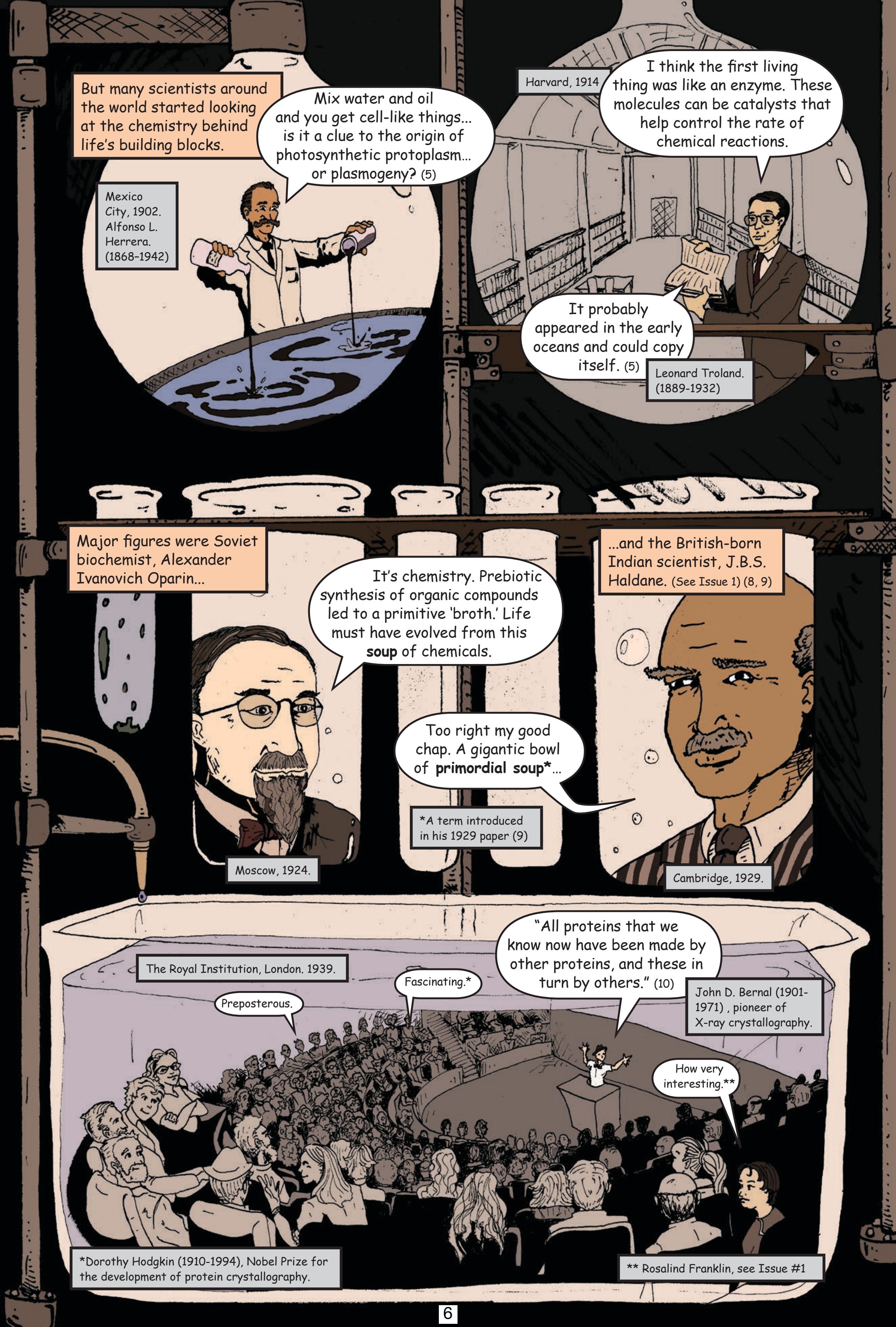
-Linda Billings, Editor

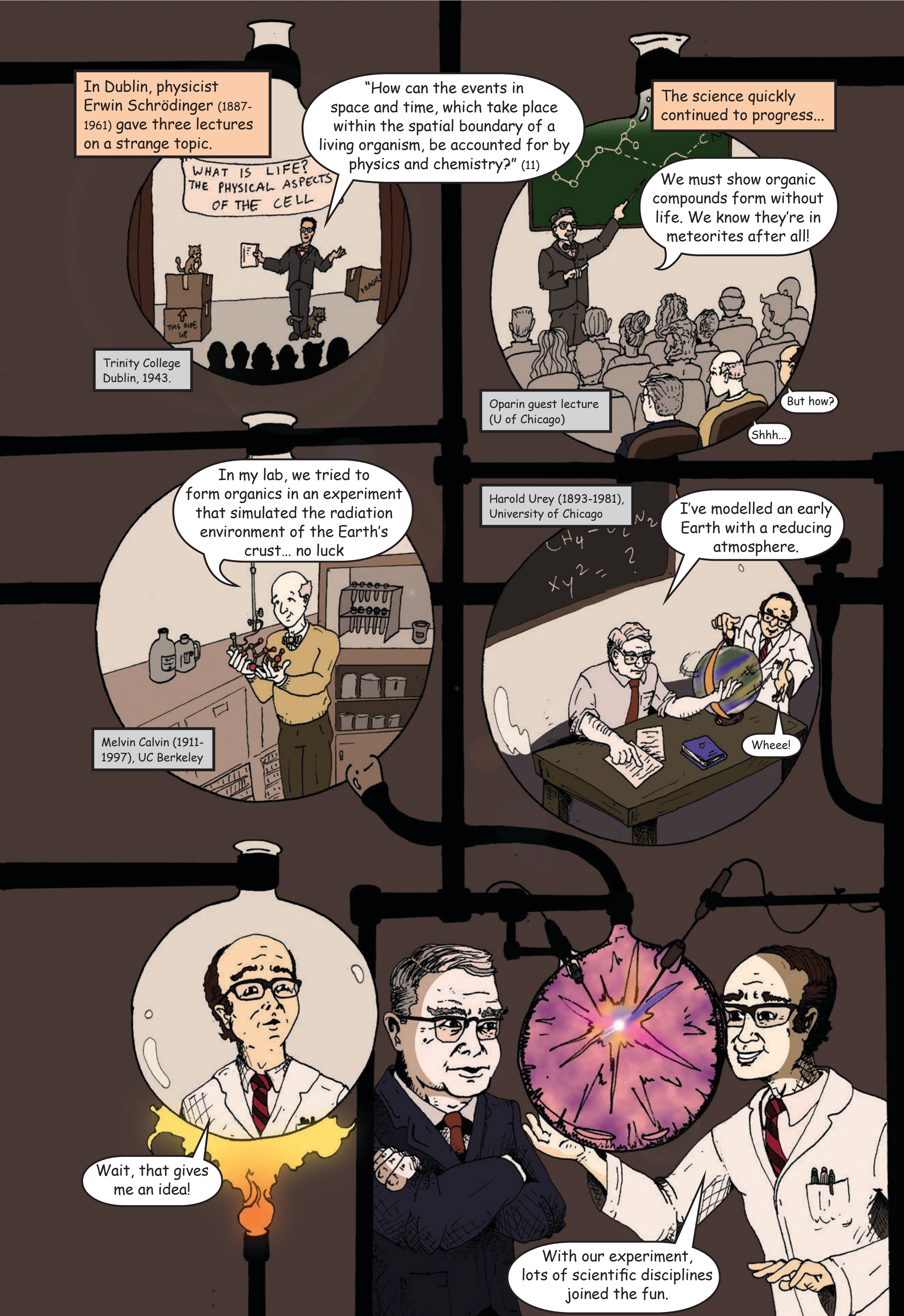

Astrobiology is the study of life's potential in the Universe.
Astrobiologists come from many scientific disciplines...
...and they use all the scientific tools at their disposal to understand life's role in the cosmos.

We have studied the Earth, the Solar System, and planets around distant stars as we search for knowledge about life.
Nathaniel Virgo, Earth Life Science Institute (ELSI)
But in order to understand life's potential out there, we have to figure out how it started here on Earth!
Sarah Maurer, Central Connecticut State University
Right! We need to study the origin of life on Earth if we want to know **if** and **how** life could gain a foothold on other worlds.
Irena Mamajanov, ELSI
Well, 'life as we know it' anyway.
Sara Walker, Arizona State University (ASU)
The study of how life began on Earth offers information we can use to consider the possibilities for the existence of life elsewhere. Origin of Life research is at the core of astrobiology.
Mary Voytek, Director of the Astrobiology Program, NASA HQ
Issue 7—Prebiotic Chemistry and the Origin of Life.

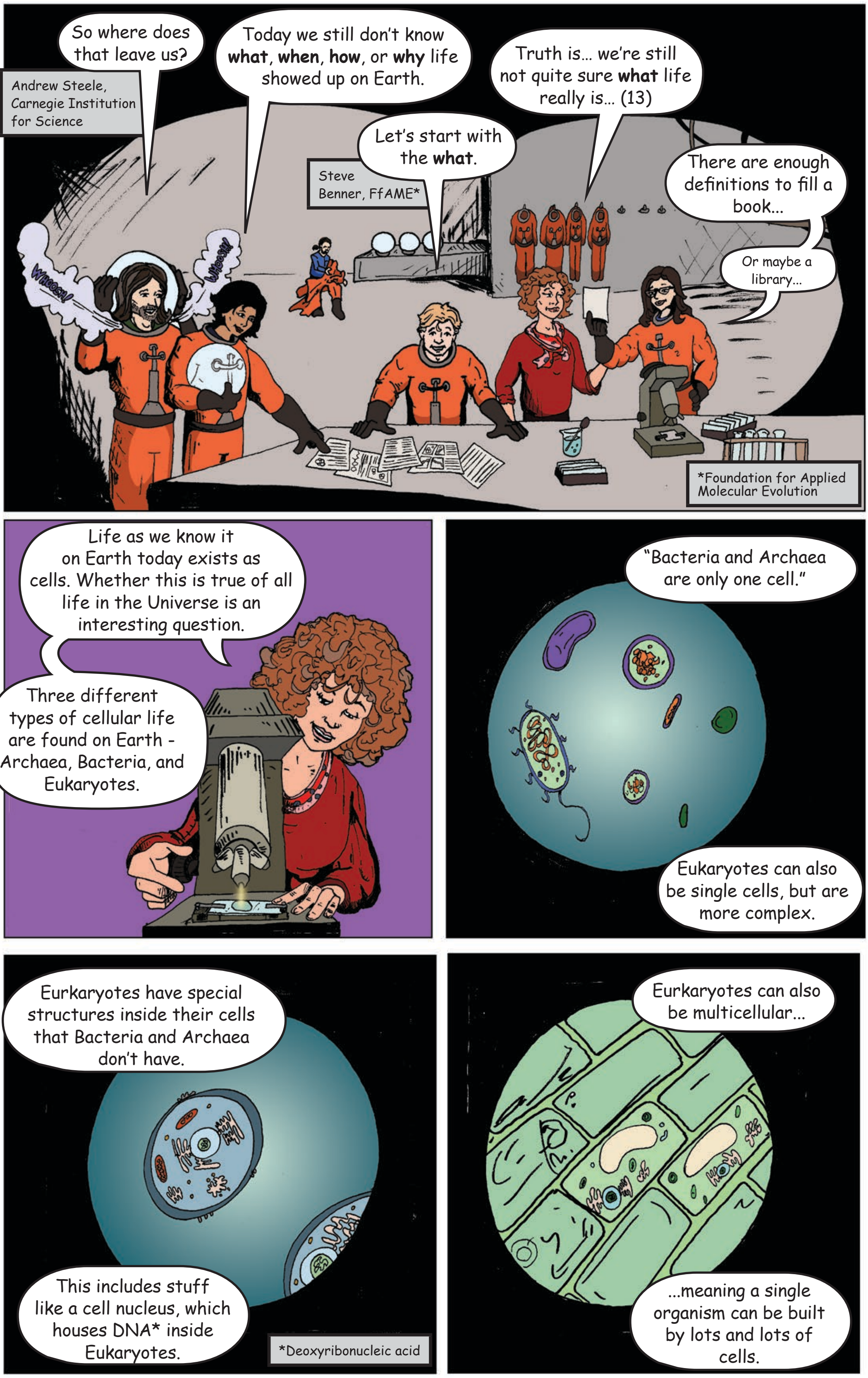

Studying the origin of life starts with life's simplest form...the **cell**.
Jeffrey Bada, Scripps Institution of Oceanography, University of California, San Diego (UCSD)
All living cells are built from the same basic pieces.
Understanding the origin of life means understanding how these pieces were used to build the first living cell. (1,2)
And to do that, we need to figure out where these pieces came from.
This is where the science of prebiotic chemistry meets astrobiology.
The field of prebiotic chemistry effectively began with the publication of Stanley Miller's paper in 1953*. (3,4)
Carol Cleland, Univ. of Colorado at Boulder
With a spark of electricity in a mix of reducing gases, Miller made some of life's most basic building blocks.
Chris Chyba, Princeton University
Stanley Miller 1930-2007
My experiment kick-started modern prebiotic chemistry research...
...but the story doesn't start there.
*See Issue #1!

Friedrich Wöhler (1800-1882) was the first to get an organic compound from inorganic materials. (5)
Urea can be formed by heating ammonium cyanate...
Was?
Ihr hat nicht alle Tassen in der Schrank...
No animal kidney necessary!
Berliner Gewerbeschule, Germany. 1828
French scientist Louis Pasteur (1822-1895) made a major step in 1859...
Sorbonne Université Paris, France
"Never will the doctrine of spontaneous generation recover" from this mortal blow!
With a simple 'swan-neck flask' experiment... (6)
...Pasteur proved that life did not simply appear from nowhere.
Bacteria doesn't just 'spontaneously' generate in sterile liquid. If you leave the flask open, it comes in from the air.
A bent top on the flask prevents bacteria getting in... and the liquid stays sterile.
Around this time, Charles Darwin (1809-1882) proposed his famous theory of life's evolution.
Although quiet on life's origins, he discussed ideas with colleagues. (7)
Of course, not every-one was a fan. (4)
Evolution? Bah!
Life rode from space on a meteorite!
London, 1871. Lord Kelvin (1825-1907).
Neugierig...
Ja. Das ist ein gute idea...
Hermann von Helm-holtz (1821-1894)
Svante Arrhenius (1859-1927).


But many scientists around the world started looking at the chemistry behind life's building blocks.
Mix water and oil and you get cell-like things... is it a clue to the origin of photosynthetic protoplasm... or plasmogeny? (5)
Mexico City, 1902. Alfonso L. Herrera. (1868–1942)
Harvard, 1914
I think the first living thing was like an enzyme. These molecules can be catalysts that help control the rate of chemical reactions.
It probably appeared in the early oceans and could copy itself. (5)
Leonard Troland. (1889-1932)
Major figures were Soviet biochemist, Alexander Ivanovich Oparin...
It's chemistry. Prebiotic synthesis of organic compounds led to a primitive 'broth.' Life must have evolved from this **soup** of chemicals.
Moscow, 1924.
...and the British-born Indian scientist, J.B.S. Haldane. (See Issue 1) (8, 9)
Too right my good chap. A gigantic bowl of **primordial soup***...
*A term introduced in his 1929 paper (9)
Cambridge, 1929.
The Royal Institution, London. 1939.
Preposterous.
Fascinating.*
"All proteins that we know now have been made by other proteins, and these in turn by others." (10)
John D. Bernal (1901-1971) , pioneer of X-ray crystallography.
How very interesting.**
*Dorothy Hodgkin (1910-1994), Nobel Prize for the development of protein crystallography.
** Rosalind Franklin, see Issue #1

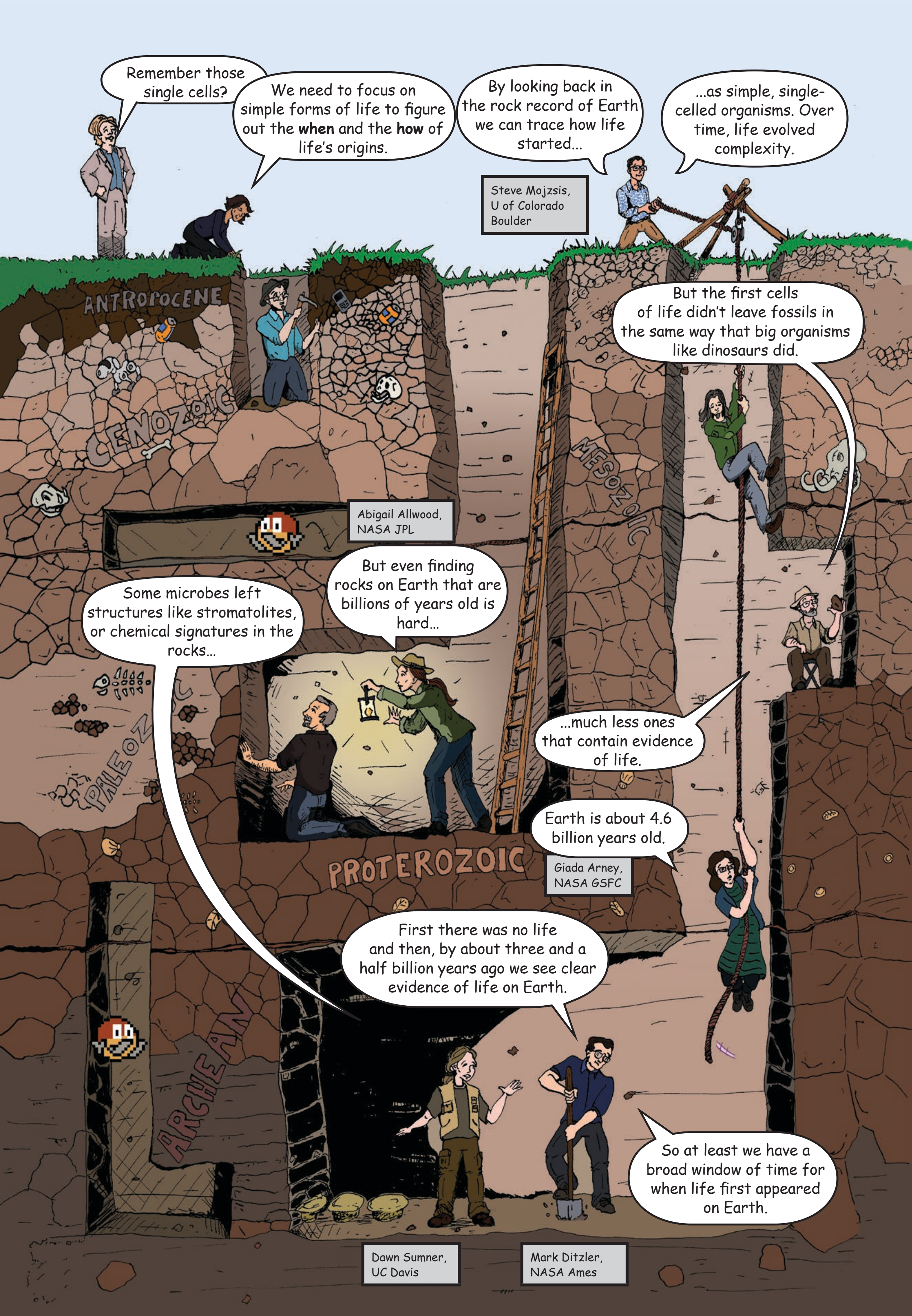

In Dublin, physicist Erwin Schrödinger (1887-1961) gave three lectures on a strange topic.
"How can the events in space and time, which take place within the spatial boundary of a living organism, be accounted for by physics and chemistry?" (11)
WHAT IS LIFE? THE PHYSICAL ASPECTS OF THE CELL
FRAGILE
THIS SIDE UP
Trinity College Dublin, 1943.
The science quickly continued to progress...
We must show organic compounds form without life. We know they're in meteorites after all!
Oparin guest lecture (U of Chicago)
But how?
Shhh...
In my lab, we tried to form organics in an experiment that simulated the radiation environment of the Earth's crust... no luck
Melvin Calvin (1911-1997), UC Berkeley
Harold Urey (1893-1981), University of Chicago
I've modelled an early Earth with a reducing atmosphere.
Wheee!
Wait, that gives me an idea!
With our experiment, lots of scientific disciplines joined the fun.


By the 1950s, scientists studying prebiotic chemistry began to join forces with molecular biologists.
Only together can we solve the question of life's origins!
When the Sputnik launch ushered in the Space Age*...
...a new era in origin of life research began.
*See Issue #1!
We must look to the stars.
Life might have appeared out there whenever the conditions were right! (12)
WHOOSH
Life in the UNIVERSE by OPARIN and FESENKOV
Michael New, NASA Science Mission Directorate (SMD)
Space exploration turned the question of extraterrestrial life into a serious area of study.
And that fueled studies on the origin of life.
Betul Kacar, University of Arizona
NASA provided substantial funding from the outset.
It was a real boon for the science.
Dave Deamer, UC Santa Cruz

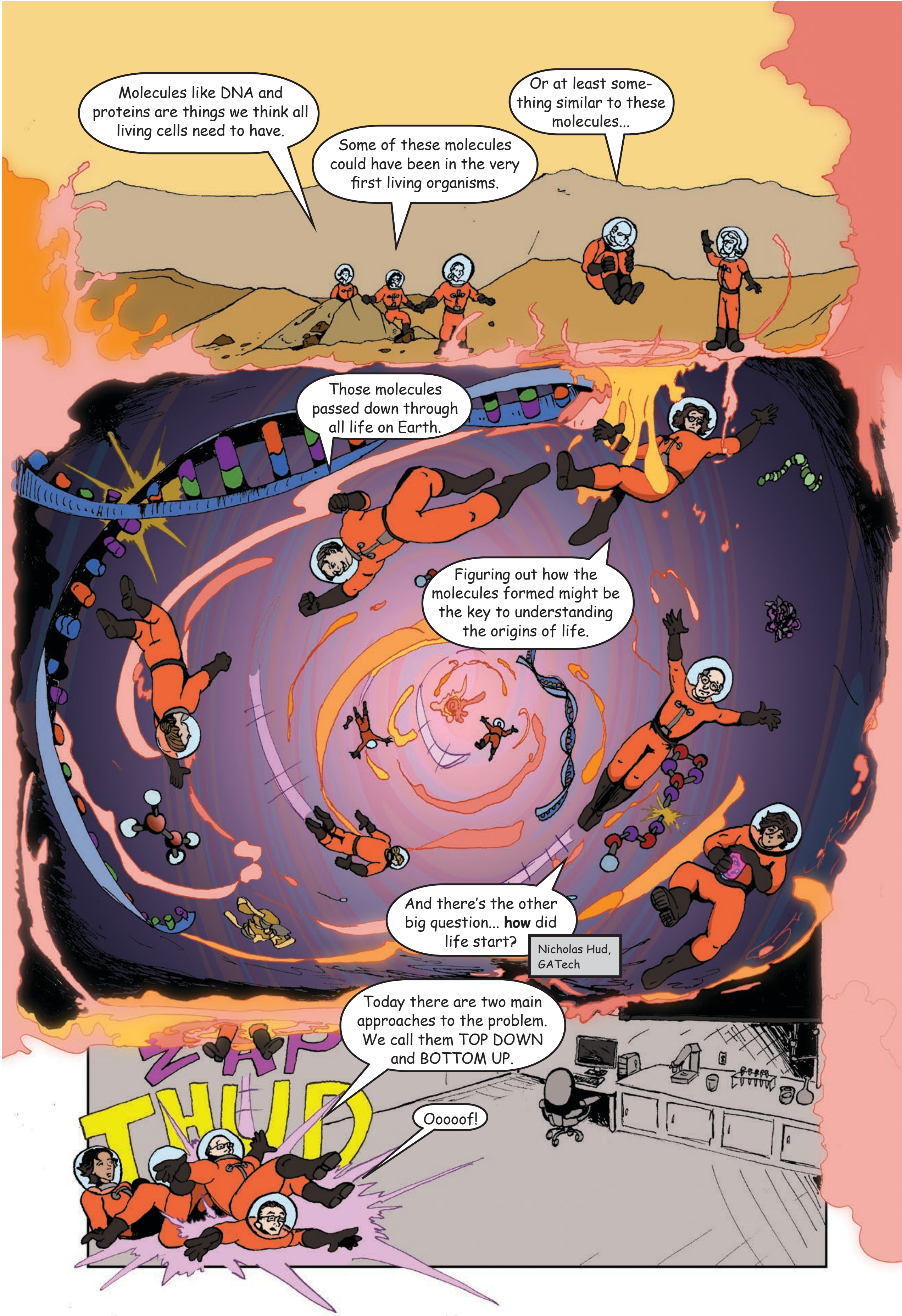


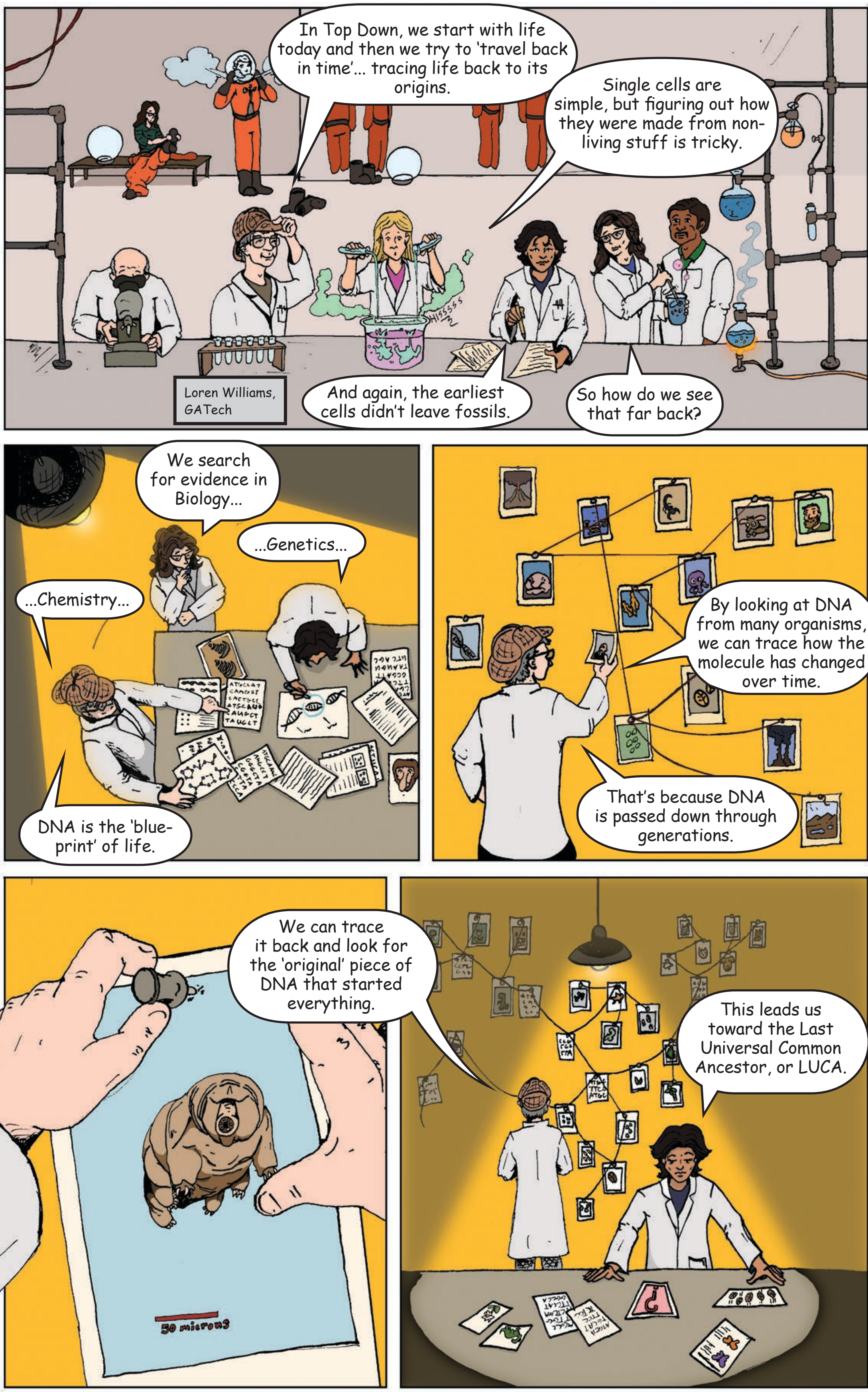
Andrew Steele, Carnegie Institution for Science
So where does that leave us?
Today we still don't know **what**, **when**, **how**, or **why** life showed up on Earth.
Truth is... we're still not quite sure **what** life really is... (13)
WHOOSH!
WHOOSH!
Steve Benner, FfAME*
Let's start with the **what**.
There are enough definitions to fill a book...
Or maybe a library...
*Foundation for Applied Molecular Evolution
Life as we know it on Earth today exists as cells. Whether this is true of all life in the Universe is an interesting question.
Three different types of cellular life are found on Earth - Archaea, Bacteria, and Eukaryotes.
"Bacteria and Archaea are only one cell."
Eukaryotes can also be single cells, but are more complex.
Eurkaryotes have special structures inside their cells that Bacteria and Archaea don't have.
This includes stuff like a cell nucleus, which houses DNA* inside Eukaryotes.
*Deoxyribonucleic acid
Eurkaryotes can also be multicellular...
...meaning a single organism can be built by lots and lots of cells.

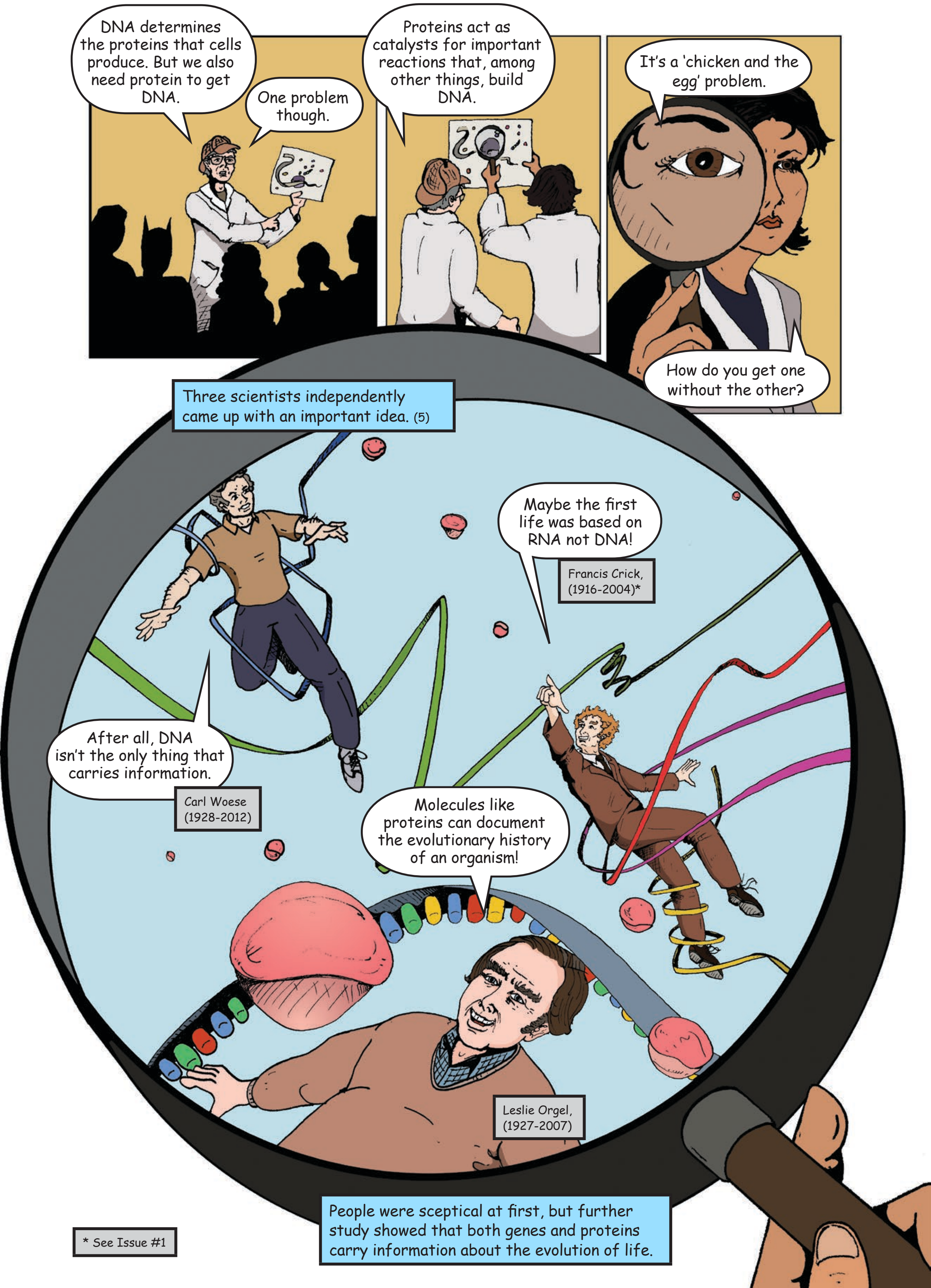

Roger Summons, Massachusetts Institute of Technology (MIT)
In eukaryotes, cells can work together to make big, complex organisms like trees!
Mary Droser, UC Riverside
Or dogs...
Woof!
...cats...
meow.
Roger Buick, U of Washington
meow.
...and walruses...
Jim Cleaves, ELSI
...or DINOSAURS!
Betul, be careful!
Oh he's fine...
These are all examples of complex life.
And, of course, humans come from this branch of the tree of life too.
BOOM!
You can put me down now, Sara.
Laurie Barge, NASA JPL
But life didn't start as complex.
Karyn Rogers, Rensselaer Polytechnic Institute (RPI)


Remember those single cells?
We need to focus on simple forms of life to figure out the **when** and the **how** of life's origins.
By looking back in the rock record of Earth we can trace how life started...
Steve Mojzsis, U of Colorado Boulder
...as simple, single-celled organisms. Over time, life evolved complexity.
ANTROPOCENE
But the first cells of life didn't leave fossils in the same way that big organisms like dinosaurs did.
CENOZOIC
MESOZOIC
Abigail Allwood, NASA JPL
But even finding rocks on Earth that are billions of years old is hard...
Some microbes left structures like stromatolites, or chemical signatures in the rocks...
...much less ones that contain evidence of life.
Earth is about 4.6 billion years old.
Giada Arney, NASA GSFC
PROTEROZOIC
First there was no life and then, by about three and a half billion years ago we see clear evidence of life on Earth.
ARCHEAN
So at least we have a broad window of time for when life first appeared on Earth.
Dawn Sumner, UC Davis
Mark Ditzler, NASA Ames

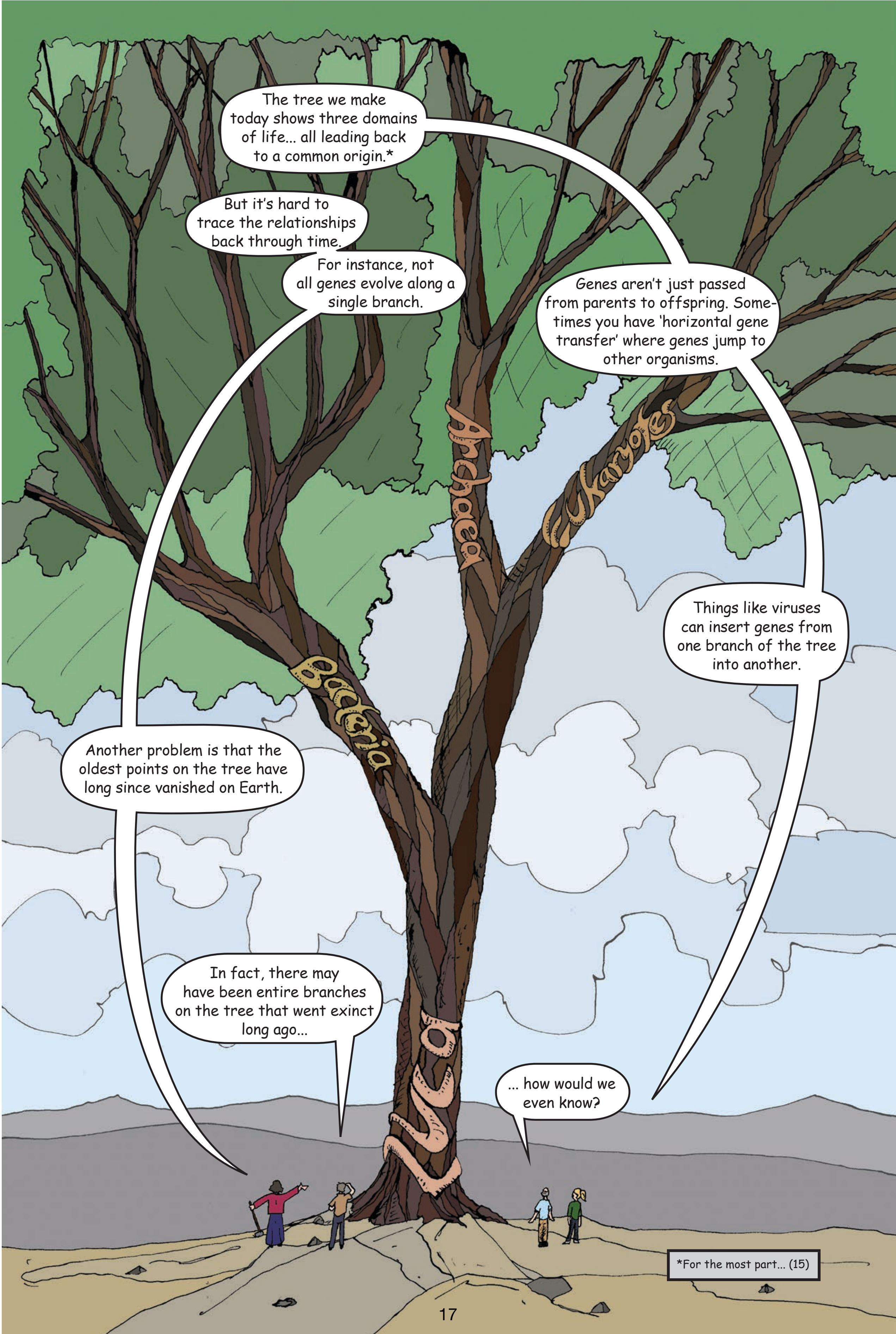
This is the Archean Eon. This is probably when something happened on Earth to give us life.
If only we could go back in time to see what it was like...
Well... we can at least try to imagine it.
Imagine if we had a portal to the past...
Welcome to the ancient Earth!*
It's like an alien world!
ZZZAPP!
This is where the origins of life happened.
By the end of the '60s, we realized there were two **big** problems with our knowledge of the ancient Earth.
Jack Szostak, Harvard University
*See Issue #6
We don't know what the Earth's atmosphere and ocean were like in the Archean...
... or tempera-ture... and a lot of other stuff.
Those conditions play a huge role in the chemistry of life.
We could look at cells today, and see what pieces have survived over billions of years of evolution.
Right. Stuff like DNA, RNA** and proteins.
Let's get your samples back to the lab!
**Ribonucleic acid


Molecules like DNA and proteins are things we think all living cells need to have.
Some of these molecules could have been in the very first living organisms.
Or at least something similar to these molecules...
Those molecules passed down through all life on Earth.
Figuring out how the molecules formed might be the key to understanding the origins of life.
And there's the other big question... **how** did life start?
Nicholas Hud, GATech
Today there are two main approaches to the problem. We call them TOP DOWN and BOTTOM UP.
ZAP
THUD
Ooooof!

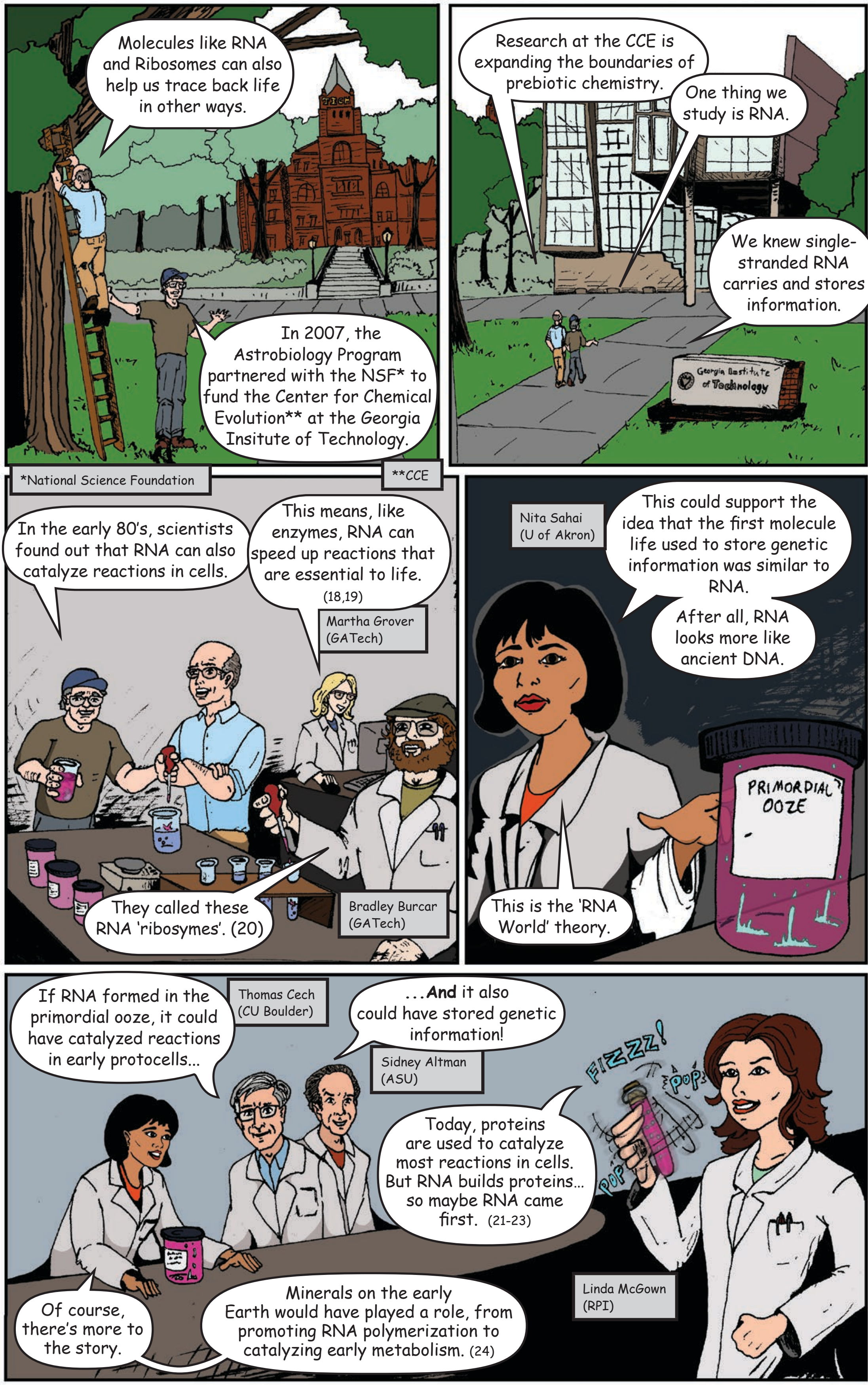

In Top Down, we start with life today and then we try to 'travel back in time'... tracing life back to its origins.
Single cells are simple, but figuring out how they were made from non-living stuff is tricky.
Loren Williams, GATech
And again, the earliest cells didn't leave fossils.
So how do we see that far back?
We search for evidence in Biology...
...Genetics...
...Chemistry...
DNA is the 'blue-print' of life.
By looking at DNA from many organisms, we can trace how the molecule has changed over time.
That's because DNA is passed down through generations.
We can trace it back and look for the 'original' piece of DNA that started everything.
50 microns
This leads us toward the Last Universal Common Ancestor, or LUCA.


DNA determines the proteins that cells produce. But we also need protein to get DNA.
One problem though.
Proteins act as catalysts for important reactions that, among other things, build DNA.
It's a 'chicken and the egg' problem.
How do you get one without the other?
Three scientists independently came up with an important idea. (5)
Maybe the first life was based on RNA not DNA!
Francis Crick, (1916-2004)*
After all, DNA isn't the only thing that carries information.
Carl Woese (1928-2012)
Molecules like proteins can document the evolutionary history of an organism!
Leslie Orgel, (1927-2007)
People were sceptical at first, but further study showed that both genes and proteins carry information about the evolution of life.
* See Issue #1

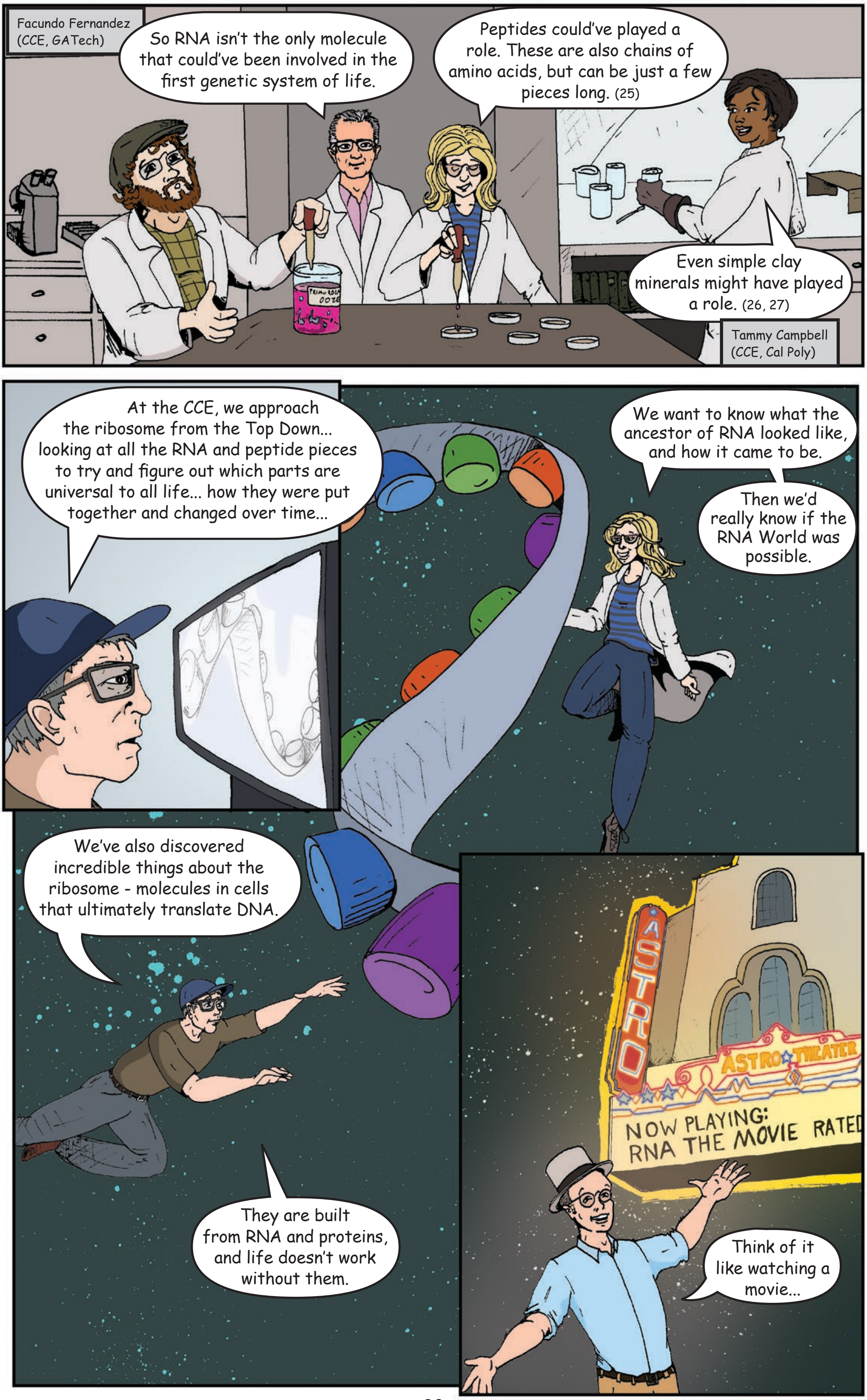

We use RNA from a molecule called the ribosome as a marker for phylogenics...
Phylogeny is like the genetic 'appearance' of an organism.*
Individual to every living thing, but with 'pages,' or genes, that get passed down in each new edition.
It's the 'book' written by our genetic code.
The small piece of RNA found in ribosomes is essential to all cells today.
So it's reasonable to think that it was also in life's first cells. (1)
*Lynn Margulis (1938-2011). Evolutionary theorist, biologist, and visionary in the study of life's evolution.
With this information, we can build a 'tree of life' based on the genetic code of organisms.
The genes we use to build this tree come from living organisms.
So we really only know the tips of the branches. Even so, we can see evolutionary relationships and shared features. (14)
Sometimes we can add information from extinct organisms if we can get a sample of their DNA...
WHOOSH!

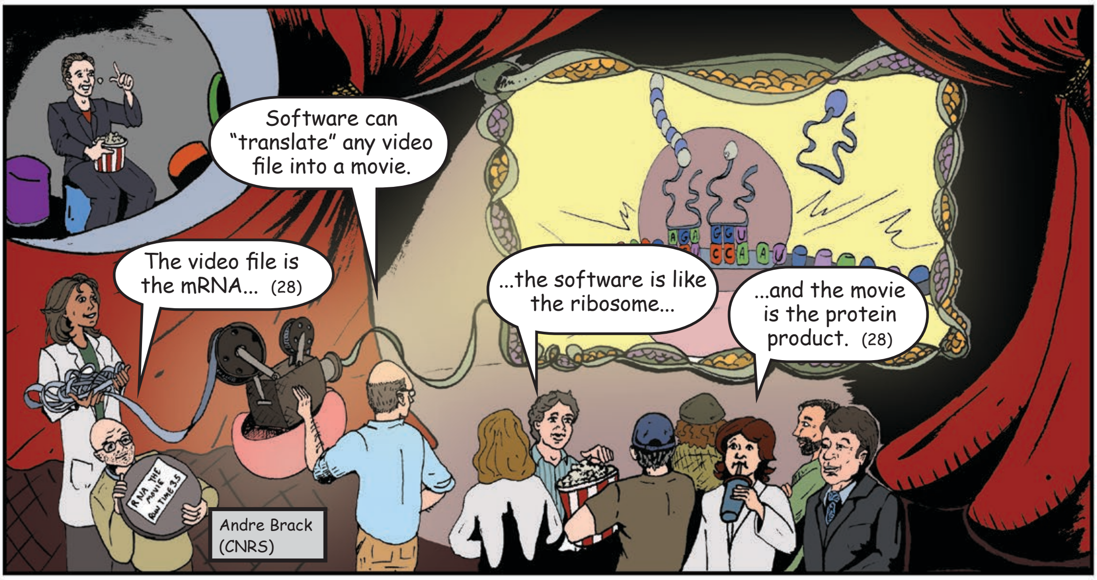

The tree we make today shows three domains of life... all leading back to a common origin.*
But it's hard to trace the relationships back through time.
For instance, not all genes evolve along a single branch.
Genes aren't just passed from parents to offspring. Sometimes you have 'horizontal gene transfer' where genes jump to other organisms.
Archaea
Eukaryotes
Bacteria
Things like viruses can insert genes from one branch of the tree into another.
Another problem is that the oldest points on the tree have long since vanished on Earth.
In fact, there may have been entire branches on the tree that went exinct long ago...
... how would we even know?
*For the most part... (15)


Climbing back along the branches of the tree of life can give us an idea of how life developed on Earth.
We can see genes that might have been found in the oldest forms of life.
Those genes could have been a single organism, or a group of interacting organisms. (16)
But it's not just genes we can look at.
Gerald Joyce (Salk Institute)
There's a lot of chemistry in the origin of life.
Chemistry is the basis of metabolic pathways in living cells, or metabolism.
All life shares the same core metabolic pathways and biochemical building blocks.
This is what we call the 'unity of biochemistry.' (16)
It means that core metabolism is ancient, and it probably dates back to the common ancestor of all life on Earth.
We estimate that LUCA lived some 3.8 to 3.5 billion years ago. (17)
Tracking back genes and metabolism can help us figure out what LUCA was like.

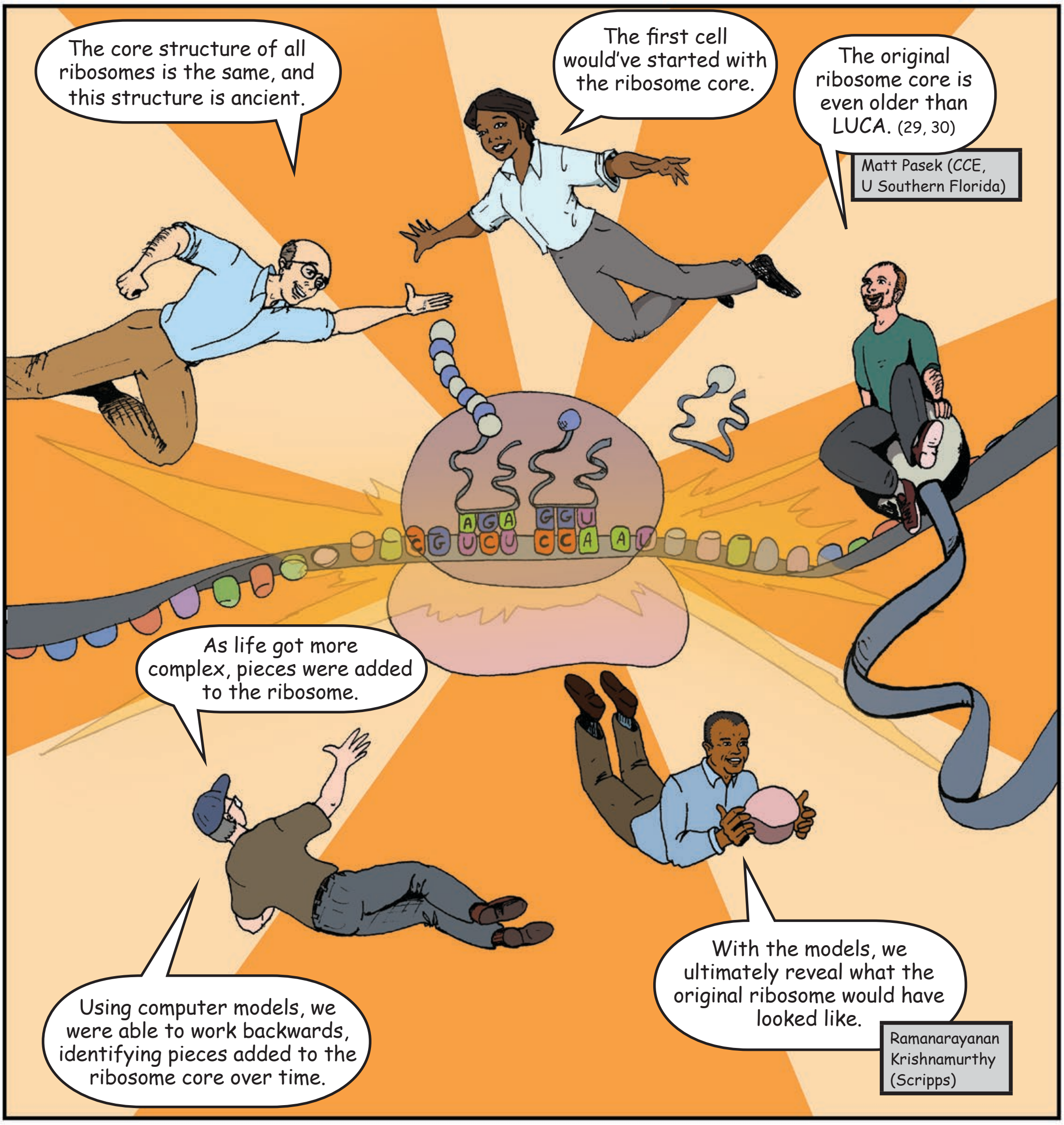


Molecules like RNA and Ribosomes can also help us trace back life in other ways.
In 2007, the Astrobiology Program partnered with the NSF* to fund the Center for Chemical Evolution** at the Georgia Insitute of Technology.
TECH
Research at the CCE is expanding the boundaries of prebiotic chemistry.
One thing we study is RNA.
We knew single-stranded RNA carries and stores information.
Georgia Institute of Technology
*National Science Foundation
**CCE
In the early 80's, scientists found out that RNA can also catalyze reactions in cells.
This means, like enzymes, RNA can speed up reactions that are essential to life. (18,19)
Martha Grover (GATech)
They called these RNA 'ribosymes'. (20)
Bradley Burcar (GATech)
Nita Sahai (U of Akron)
This could support the idea that the first molecule life used to store genetic information was similar to RNA.
After all, RNA looks more like ancient DNA.
PRIMORDIAL OOZE
This is the 'RNA World' theory.
If RNA formed in the primordial ooze, it could have catalyzed reactions in early protocells...
Thomas Cech (CU Boulder)
...**And** it also could have stored genetic information!
Sidney Altman (ASU)
FIZZZ!
POP
POP
Today, proteins are used to catalyze most reactions in cells. But RNA builds proteins... so maybe RNA came first. (21-23)
Linda McGown (RPI)
Of course, there's more to the story.
Minerals on the early Earth would have played a role, from promoting RNA polymerization to catalyzing early metabolism. (24)

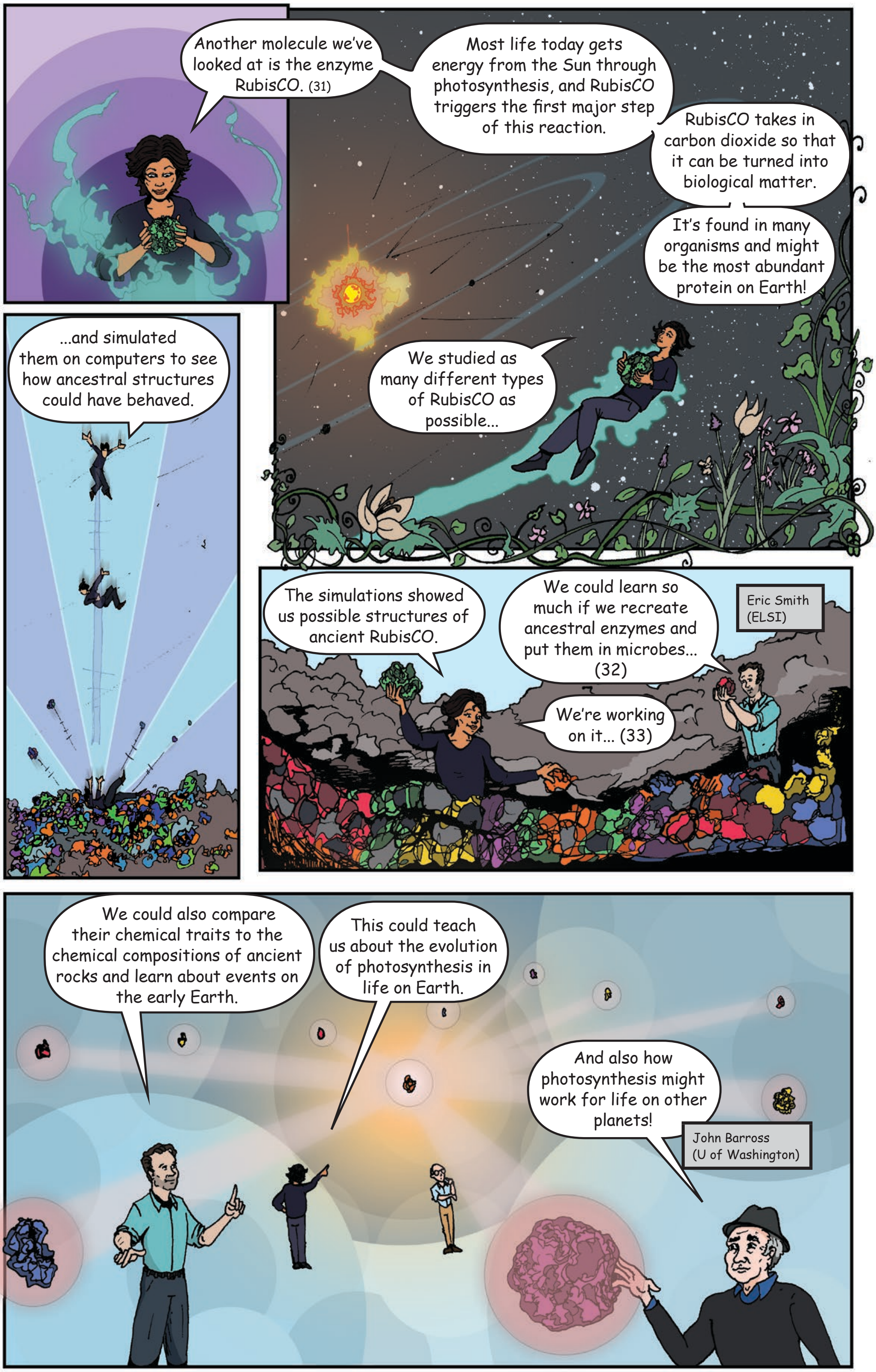

Facundo Fernandez (CCE, GATech)
So RNA isn't the only molecule that could've been involved in the first genetic system of life.
Peptides could've played a role. These are also chains of amino acids, but can be just a few pieces long. (25)
Even simple clay minerals might have played a role. (26, 27)
Tammy Campbell (CCE, Cal Poly)
At the CCE, we approach the ribosome from the Top Down... looking at all the RNA and peptide pieces to try and figure out which parts are universal to all life... how they were put together and changed over time...
We want to know what the ancestor of RNA looked like, and how it came to be.
Then we'd really know if the RNA World was possible.
We've also discovered incredible things about the ribosome - molecules in cells that ultimately translate DNA.
They are built from RNA and proteins, and life doesn't work without them.
ASTRO
ASTRO THEATER
NOW PLAYING: RNA THE MOVIE RATED
Think of it like watching a movie...



Software can "translate" any video file into a movie.
The video file is the mRNA... (28)
...the software is like the ribosome...
...and the movie is the protein product. (28)
Andre Brack (CNRS)

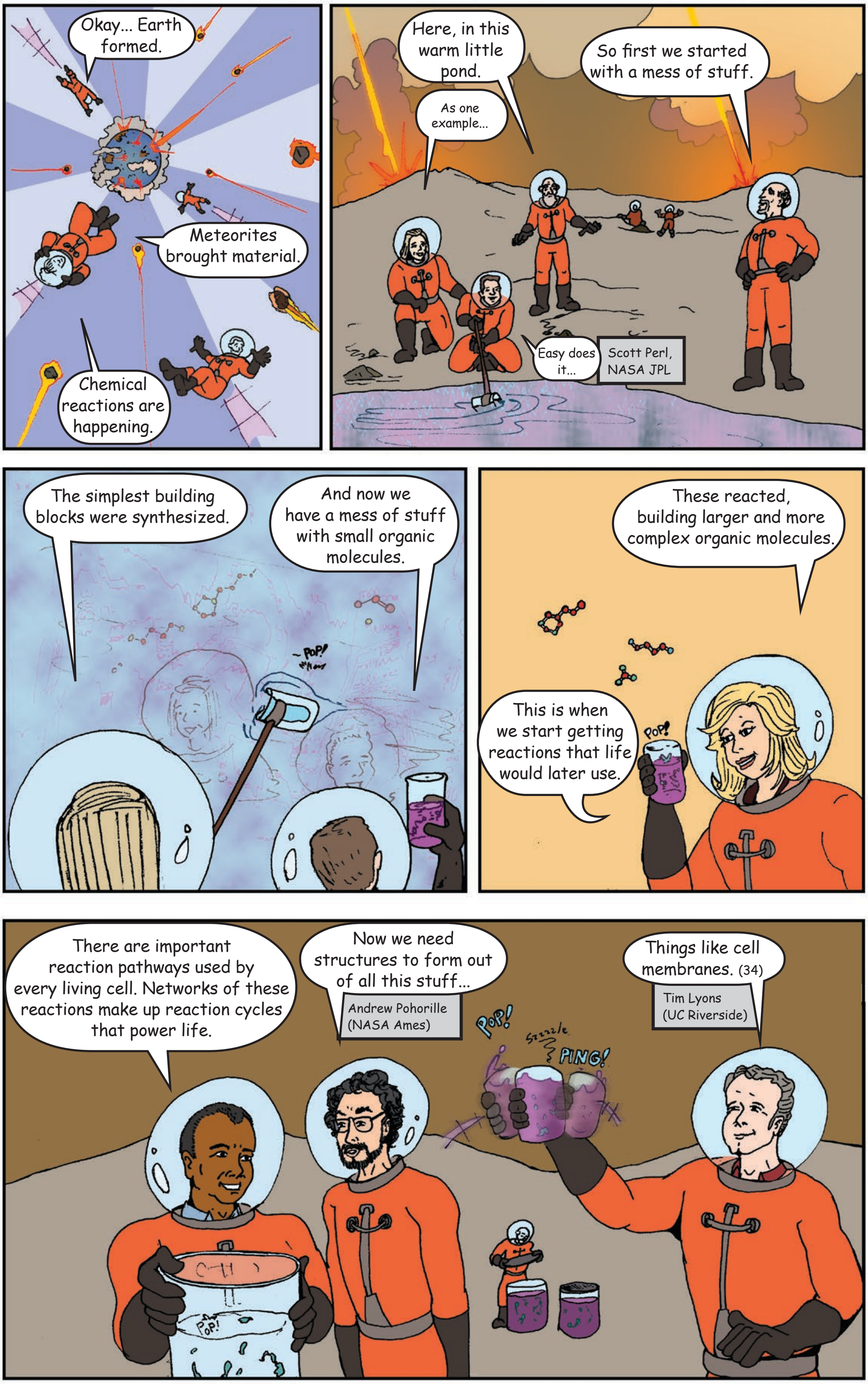


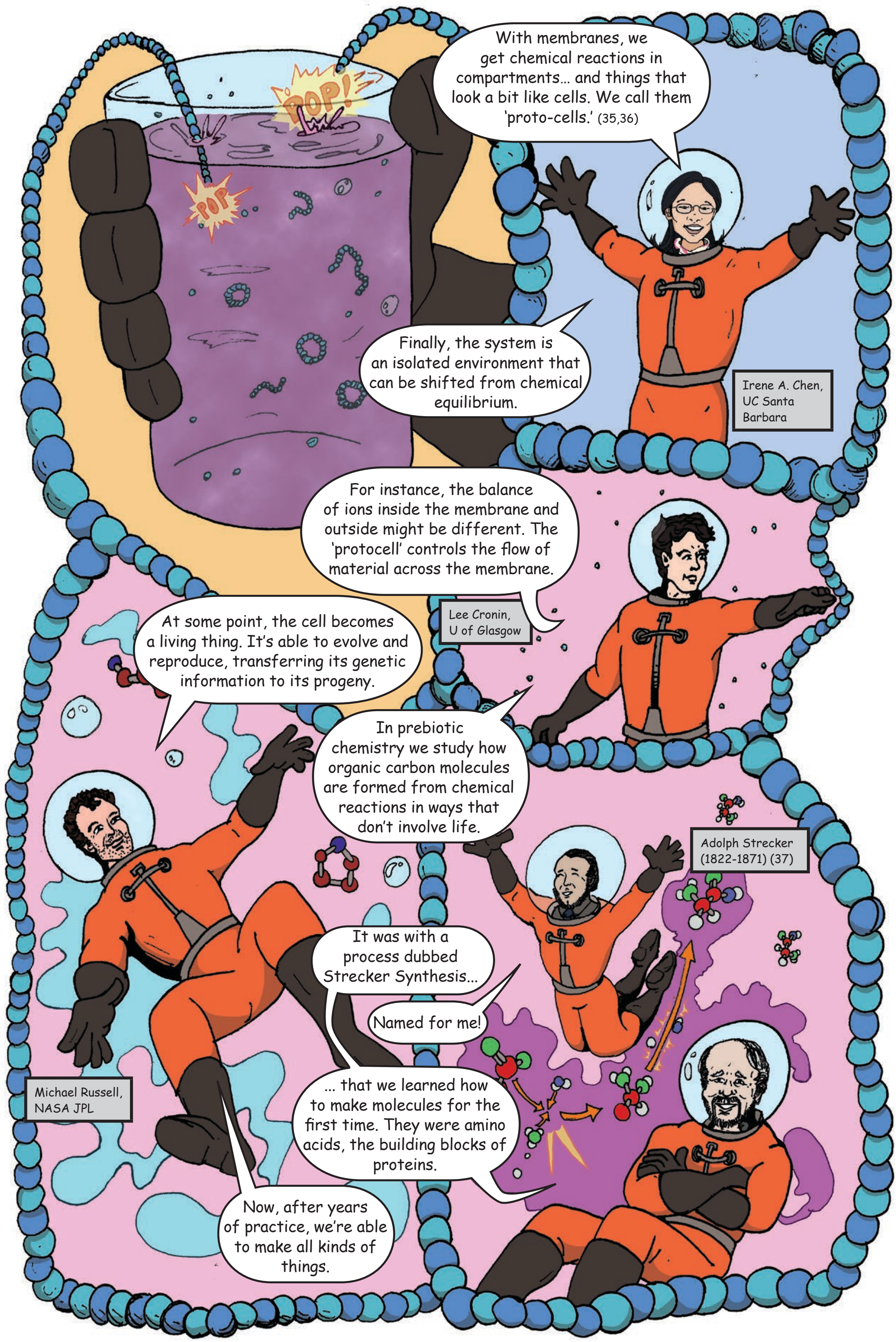
The core structure of all ribosomes is the same, and this structure is ancient.
The first cell would've started with the ribosome core.
The original ribosome core is even older than LUCA. (29, 30)
Matt Pasek (CCE, U Southern Florida)
As life got more complex, pieces were added to the ribosome.
Using computer models, we were able to work backwards, identifying pieces added to the ribosome core over time.
With the models, we ultimately reveal what the original ribosome would have looked like.
Ramanarayanan Krishnamurthy (Scripps)

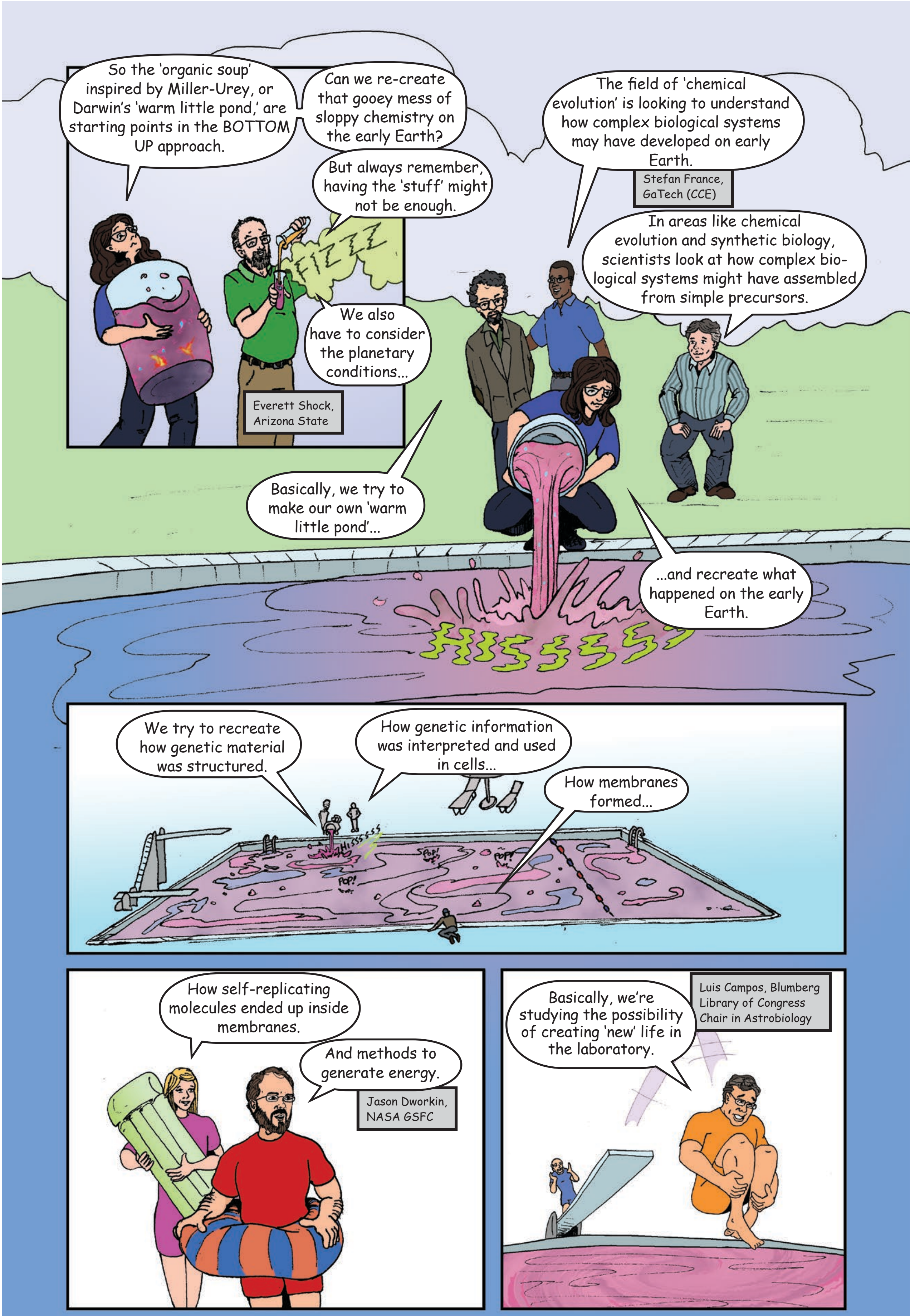

Another molecule we've looked at is the enzyme RubisCO. (31)
Most life today gets energy from the Sun through photosynthesis, and RubisCO triggers the first major step of this reaction.
RubisCO takes in carbon dioxide so that it can be turned into biological matter.
It's found in many organisms and might be the most abundant protein on Earth!
We studied as many different types of RubisCO as possible...
...and simulated them on computers to see how ancestral structures could have behaved.
The simulations showed us possible structures of ancient RubisCO.
We could learn so much if we recreate ancestral enzymes and put them in microbes... (32)
Eric Smith (ELSI)
We're working on it... (33)
We could also compare their chemical traits to the chemical compositions of ancient rocks and learn about events on the early Earth.
This could teach us about the evolution of photosynthesis in life on Earth.
And also how photosynthesis might work for life on other planets!
John Barross (U of Washington)

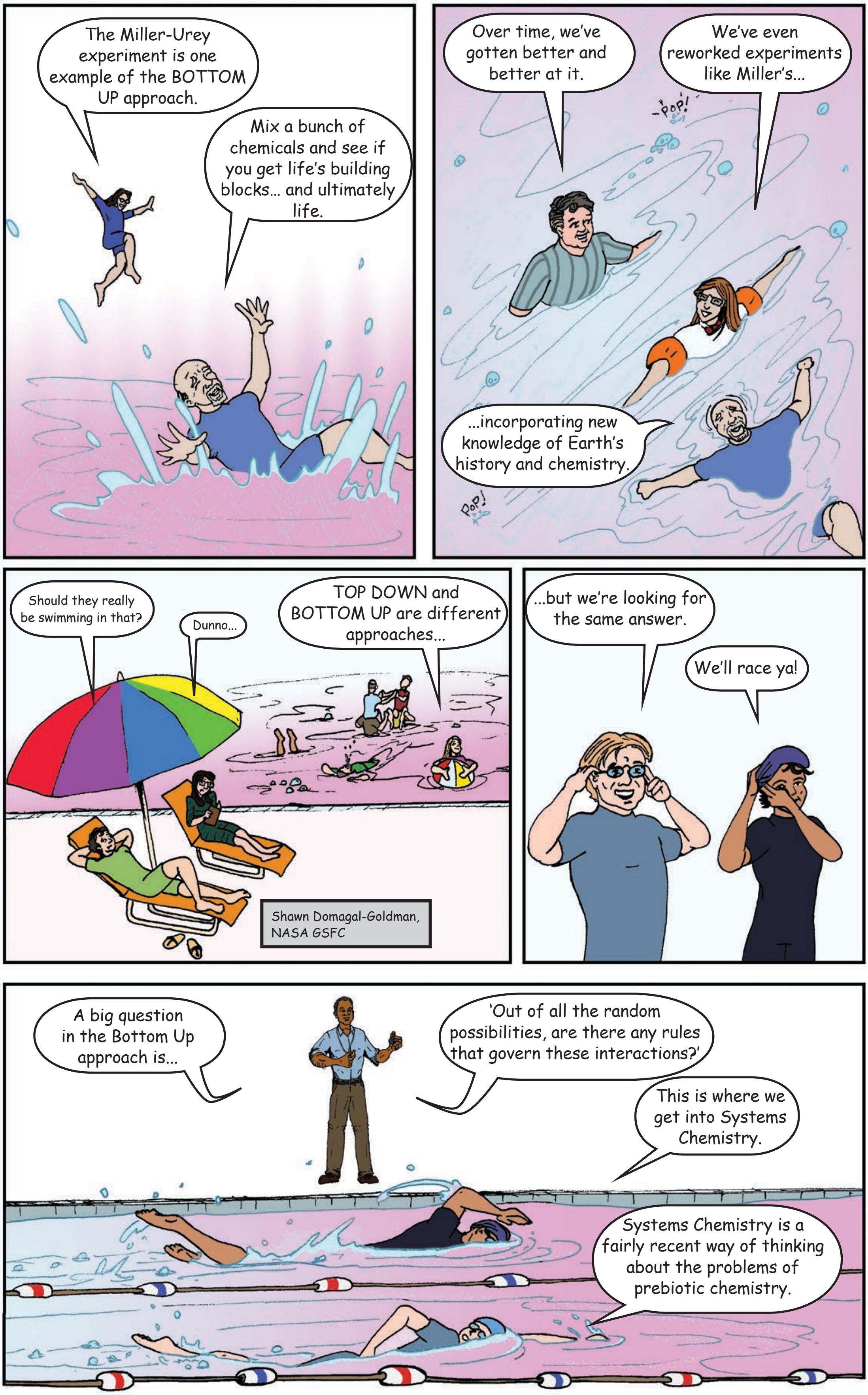

So in TOP DOWN we start with life today and work backwards.
But what if we look at the origin of life from the other direction?
That's the BOTTOM UP approach.
Michael Mumma (NASA GSFC)
Edward Grew (U of Maine)
Sarah Keller (U of Washington)
And for that, we start with nothing.
And I mean NOTHING.
What then?
BANG

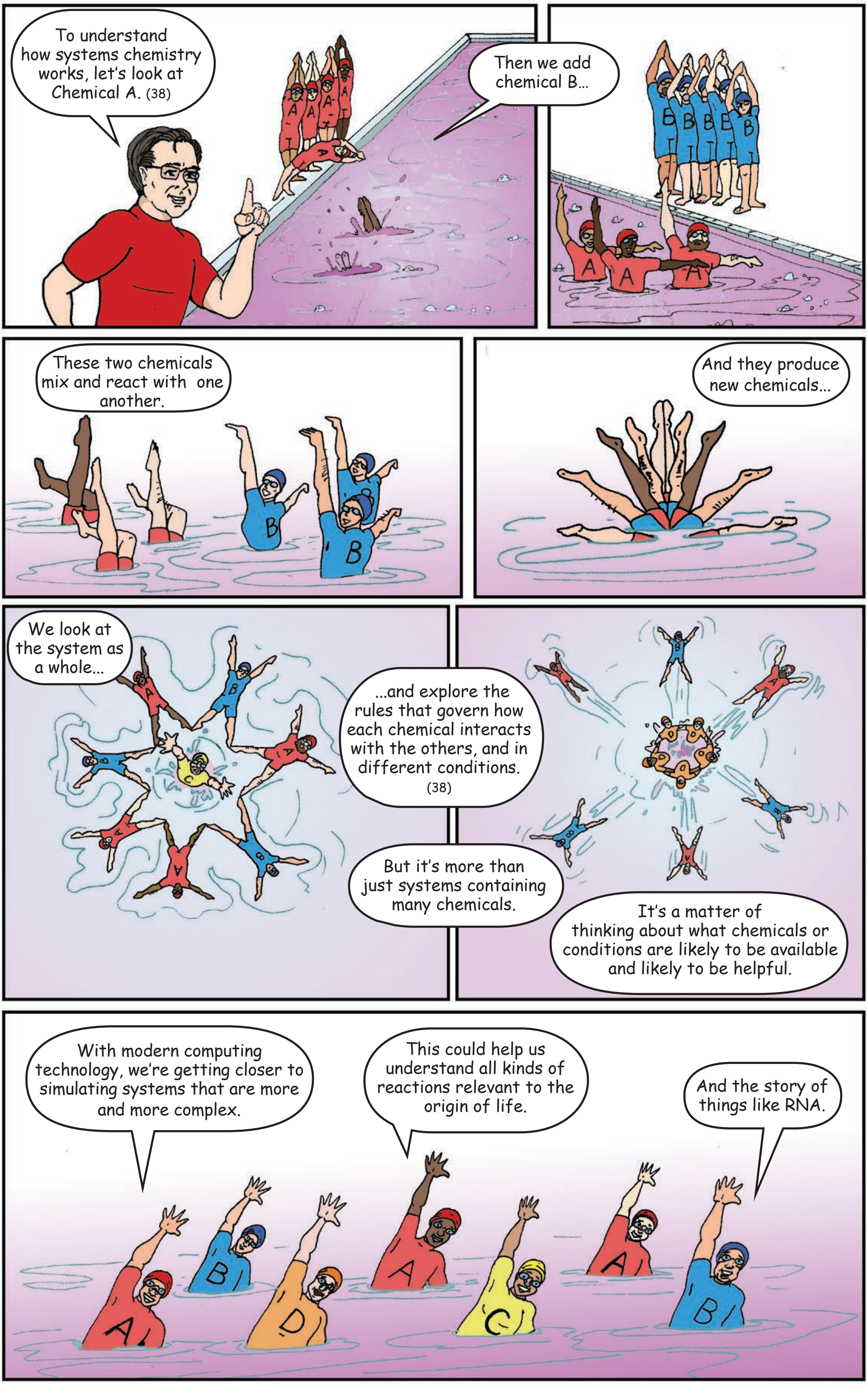

The Big Bang created the first elements.
From here, there's so many missing pieces in the story.
Like, how did we get from chemical elements formed in the Big Bang, some 13.8 billion years ago, to the molecules that make life?
Bob Hazen (Carnegie)
Cells are made from so many parts.
We need to move ahead to a time when life as we know it likely started...
...focus on the early Earth, after it formed.
Right. We need to go back to the Archaean....
Suits back on!

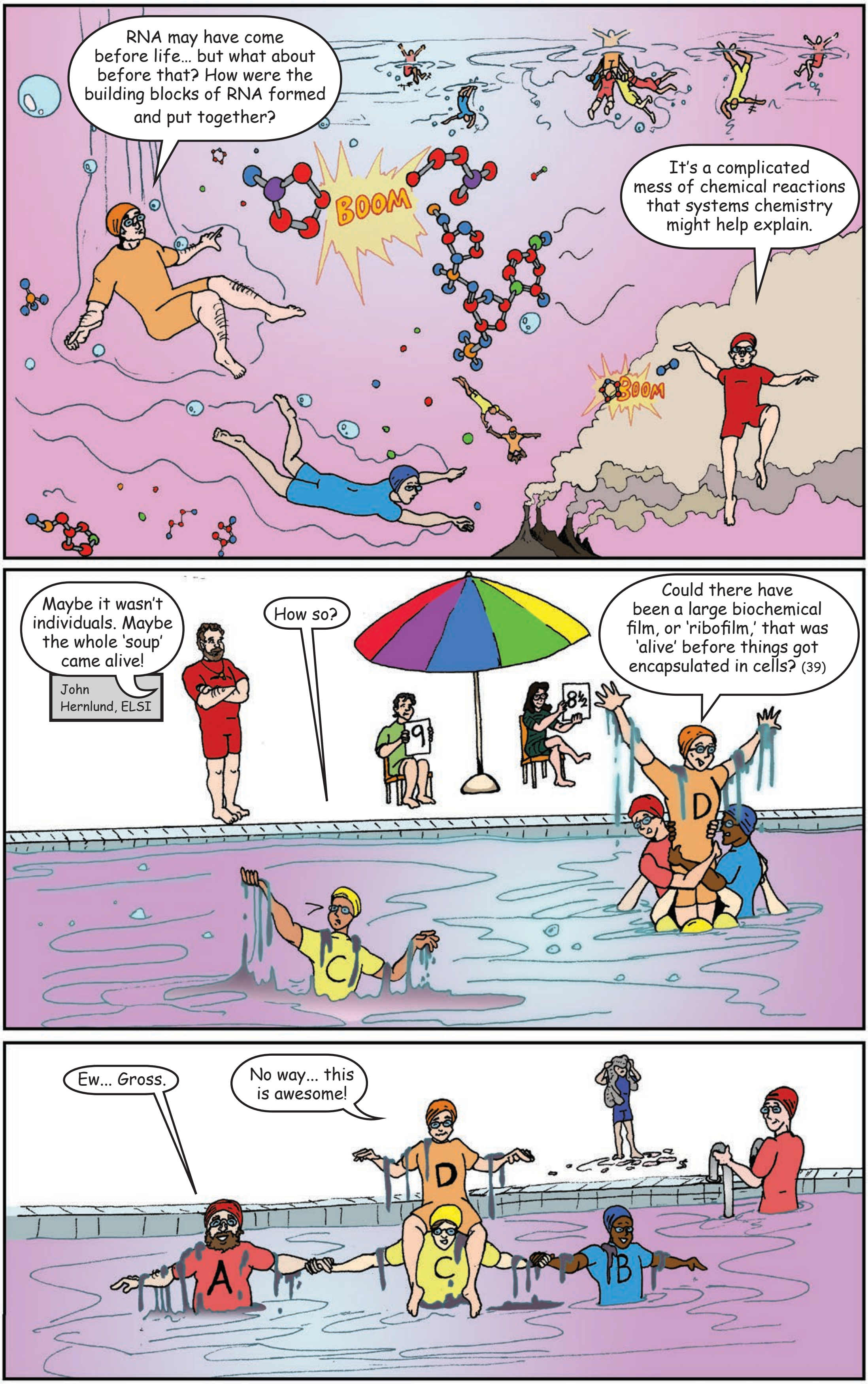

Okay... Earth formed.
Meteorites brought material.
Chemical reactions are happening.
Here, in this warm little pond.
As one example...
So first we started with a mess of stuff.
Easy does it...
Scott Perl, NASA JPL
The simplest building blocks were synthesized.
And now we have a mess of stuff with small organic molecules.
POP!
These reacted, building larger and more complex organic molecules.
This is when we start getting reactions that life would later use.
POP!
There are important reaction pathways used by every living cell. Networks of these reactions make up reaction cycles that power life.
Now we need structures to form out of all this stuff...
Andrew Pohorille (NASA Ames)
Things like cell membranes. (34)
Tim Lyons (UC Riverside)
POP!
Sizzle
PING!
POP!

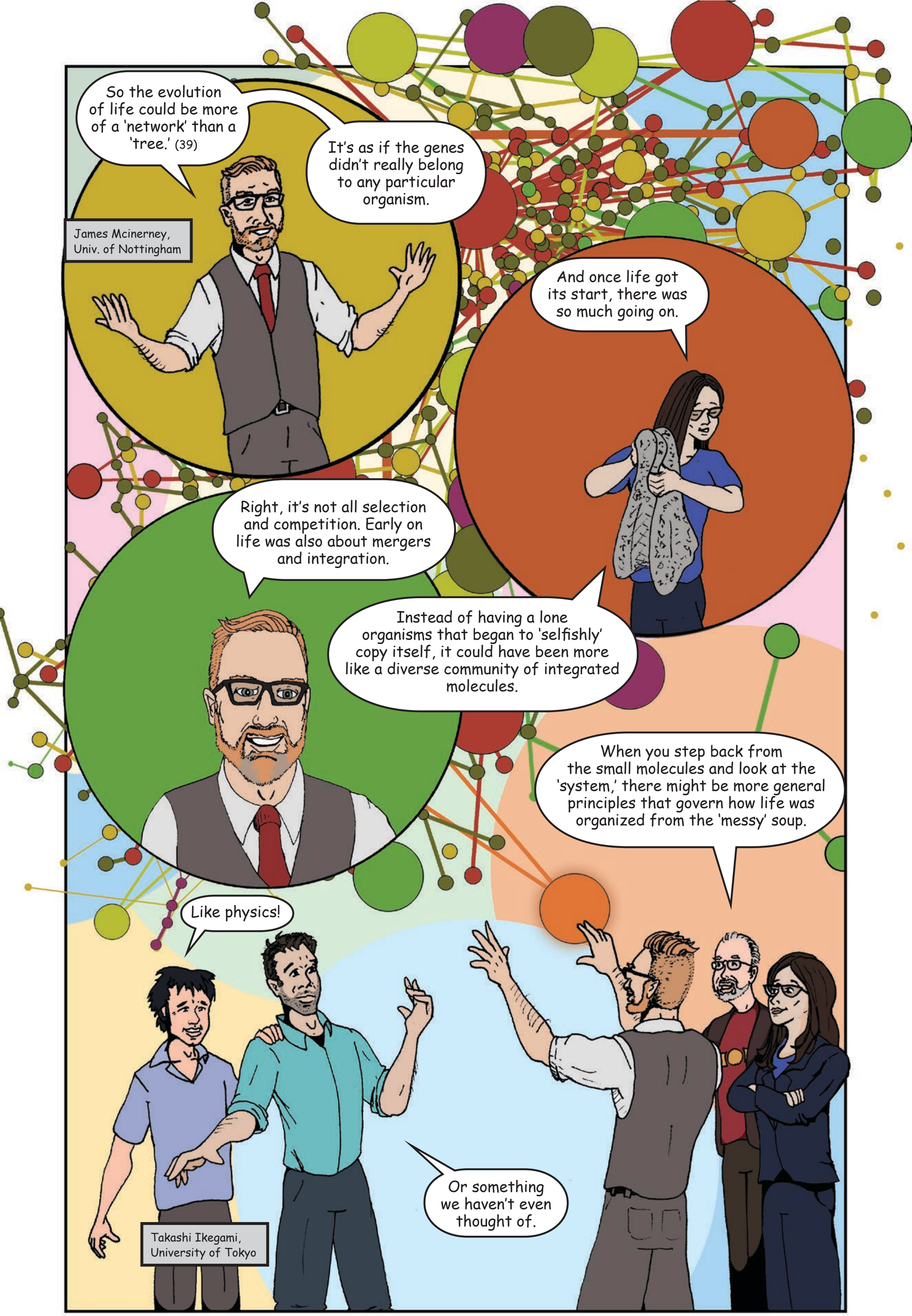

POP!
POP
With membranes, we get chemical reactions in compartments... and things that look a bit like cells. We call them 'proto-cells.' (35,36)
Finally, the system is an isolated environment that can be shifted from chemical equilibrium.
Irene A. Chen, UC Santa Barbara
For instance, the balance of ions inside the membrane and outside might be different. The 'protocell' controls the flow of material across the membrane.
Lee Cronin, U of Glasgow
At some point, the cell becomes a living thing. It's able to evolve and reproduce, transferring its genetic information to its progeny.
In prebiotic chemistry we study how organic carbon molecules are formed from chemical reactions in ways that don't involve life.
Adolph Strecker (1822-1871) (37)
It was with a process dubbed Strecker Synthesis...
Named for me!
... that we learned how to make molecules for the first time. They were amino acids, the building blocks of proteins.
Michael Russell, NASA JPL
Now, after years of practice, we're able to make all kinds of things.

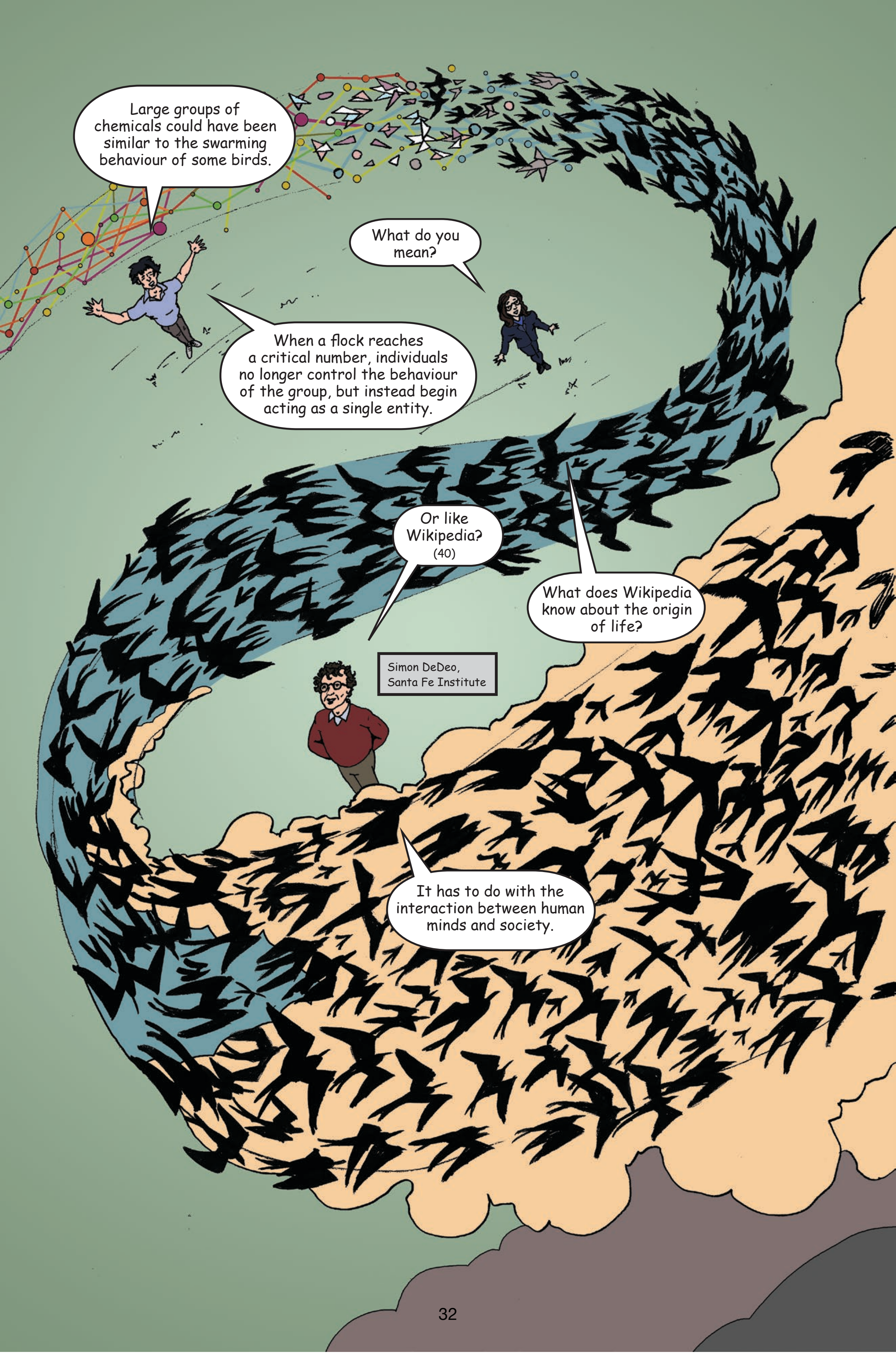

So the 'organic soup' inspired by Miller-Urey, or Darwin's 'warm little pond,' are starting points in the BOTTOM UP approach.
Can we re-create that gooey mess of sloppy chemistry on the early Earth?
But always remember, having the 'stuff' might not be enough.
FIZZZ
We also have to consider the planetary conditions...
Everett Shock, Arizona State
The field of 'chemical evolution' is looking to understand how complex biological systems may have developed on early Earth.
Stefan France, GaTech (CCE)
In areas like chemical evolution and synthetic biology, scientists look at how complex bio-logical systems might have assembled from simple precursors.
Basically, we try to make our own 'warm little pond'...
...and recreate what happened on the early Earth.
HISSSSSS
We try to recreate how genetic material was structured.
How genetic information was interpreted and used in cells...
How membranes formed...
POP!
POP!
POP!
How self-replicating molecules ended up inside membranes.
And methods to generate energy.
Jason Dworkin, NASA GSFC
Basically, we're studying the possibility of creating 'new' life in the laboratory.
Luis Campos, Blumberg Library of Congress Chair in Astrobiology

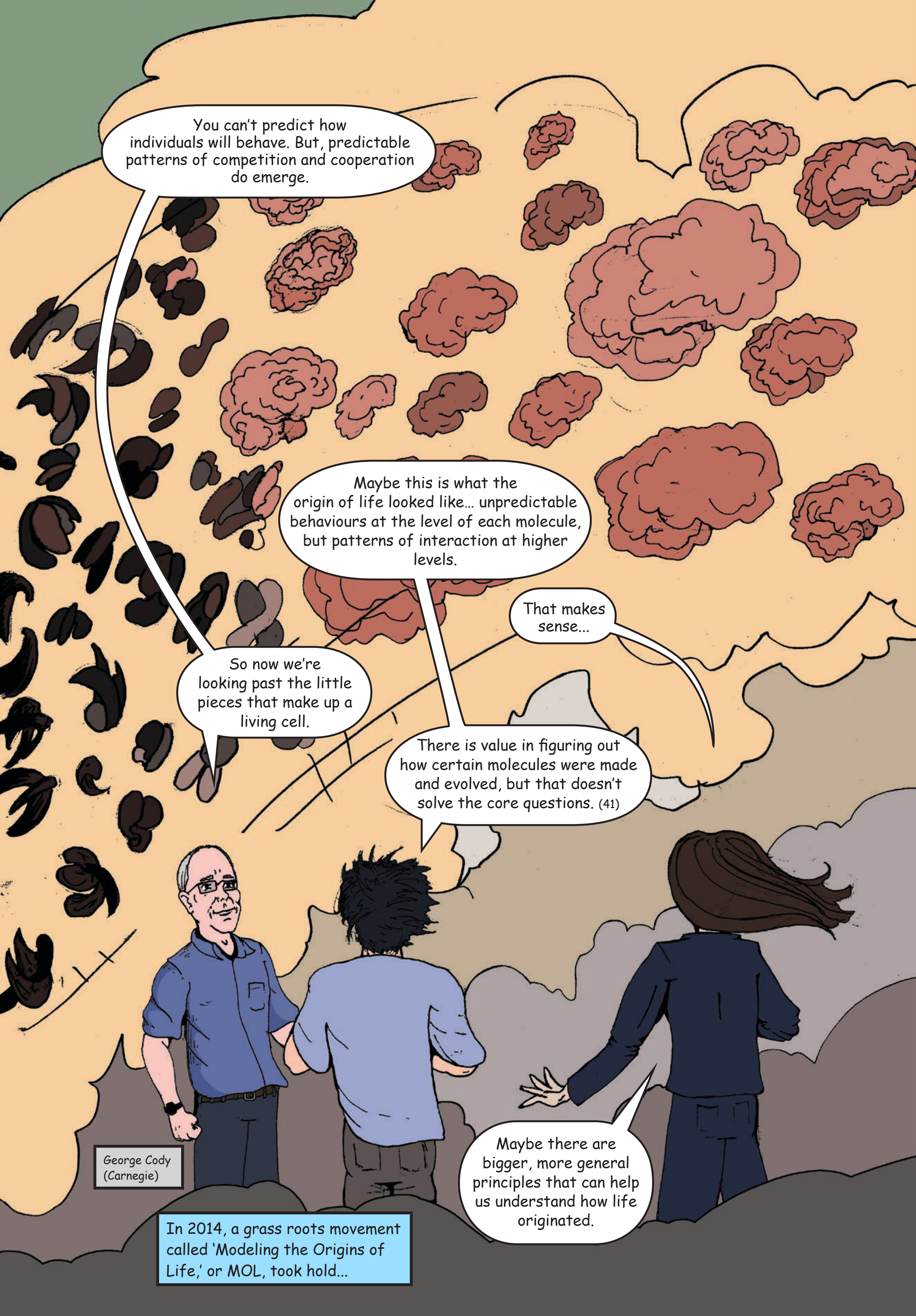

The Miller-Urey experiment is one example of the BOTTOM UP approach.
Mix a bunch of chemicals and see if you get life's building blocks... and ultimately life.
Over time, we've gotten better and better at it.
We've even reworked experiments like Miller's...
POP!
...incorporating new knowledge of Earth's history and chemistry.
POP!
Should they really be swimming in that?
Dunno...
TOP DOWN and BOTTOM UP are different approaches...
Shawn Domagal-Goldman, NASA GSFC
...but we're looking for the same answer.
We'll race ya!
A big question in the Bottom Up approach is...
'Out of all the random possibilities, are there any rules that govern these interactions?'
This is where we get into Systems Chemistry.
Systems Chemistry is a fairly recent way of thinking about the problems of prebiotic chemistry.


To understand how systems chemistry works, let's look at Chemical A. (38)
Then we add chemical B...
These two chemicals mix and react with one another.
And they produce new chemicals...
We look at the system as a whole...
...and explore the rules that govern how each chemical interacts with the others, and in different conditions. (38)
But it's more than just systems containing many chemicals.
It's a matter of thinking about what chemicals or conditions are likely to be available and likely to be helpful.
With modern computing technology, we're getting closer to simulating systems that are more and more complex.
This could help us understand all kinds of reactions relevant to the origin of life.
And the story of things like RNA.

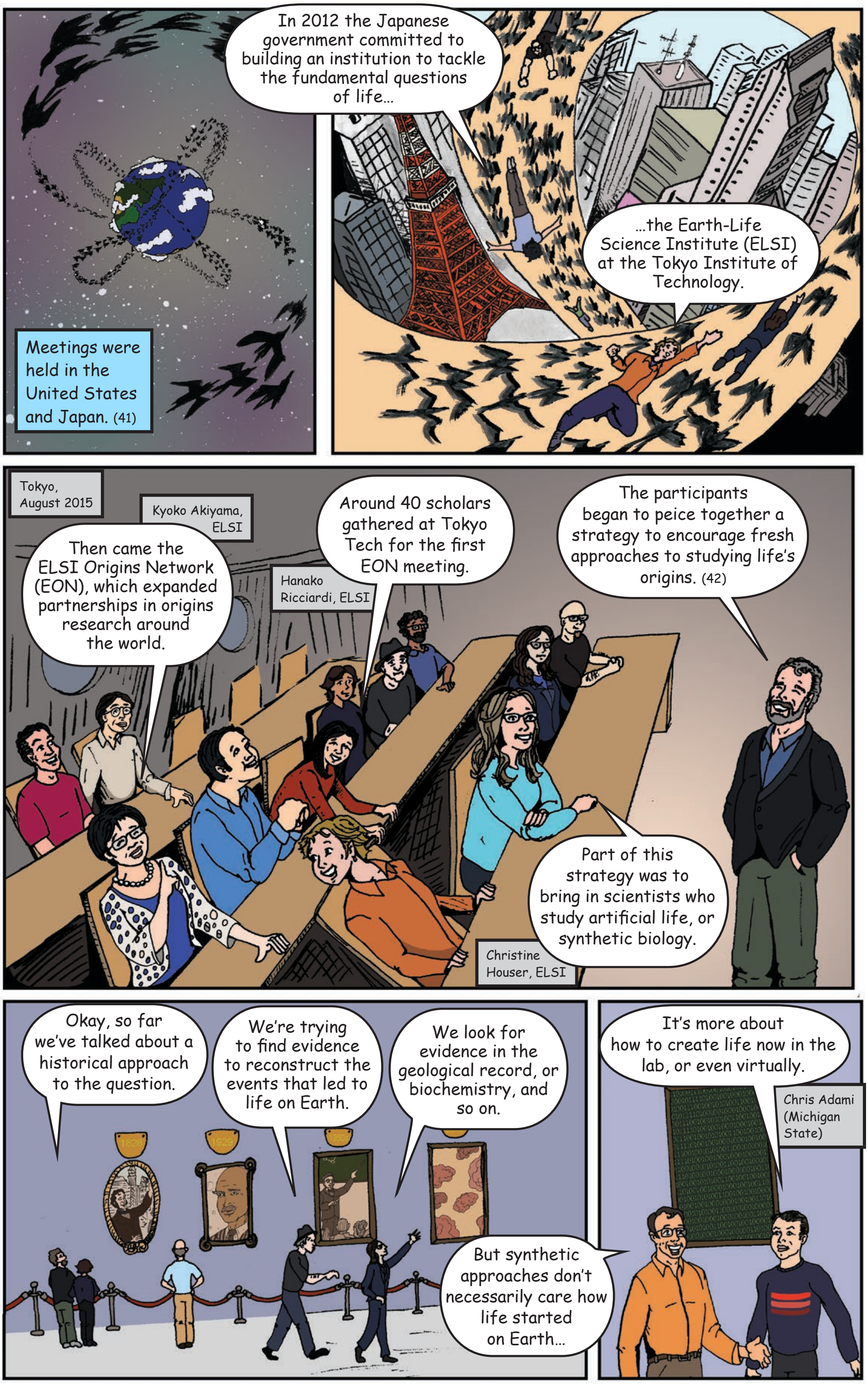

RNA may have come before life... but what about before that? How were the building blocks of RNA formed and put together?
BOOM
It's a complicated mess of chemical reactions that systems chemistry might help explain.
BOOM
Maybe it wasn't individuals. Maybe the whole 'soup' came alive!
John Hernlund, ELSI
How so?
9
8½
Could there have been a large biochemical film, or 'ribofilm,' that was 'alive' before things got encapsulated in cells? (39)
D
C
Ew... Gross.
No way... this is awesome!
D
A
C
B


So the evolution of life could be more of a 'network' than a 'tree.' (39)
It's as if the genes didn't really belong to any particular organism.
James Mcinerney, Univ. of Nottingham
And once life got its start, there was so much going on.
Right, it's not all selection and competition. Early on life was also about mergers and integration.
Instead of having a lone organisms that began to 'selfishly' copy itself, it could have been more like a diverse community of integrated molecules.
When you step back from the small molecules and look at the 'system,' there might be more general principles that govern how life was organized from the 'messy' soup.
Like physics!
Or something we haven't even thought of.
Takashi Ikegami, University of Tokyo

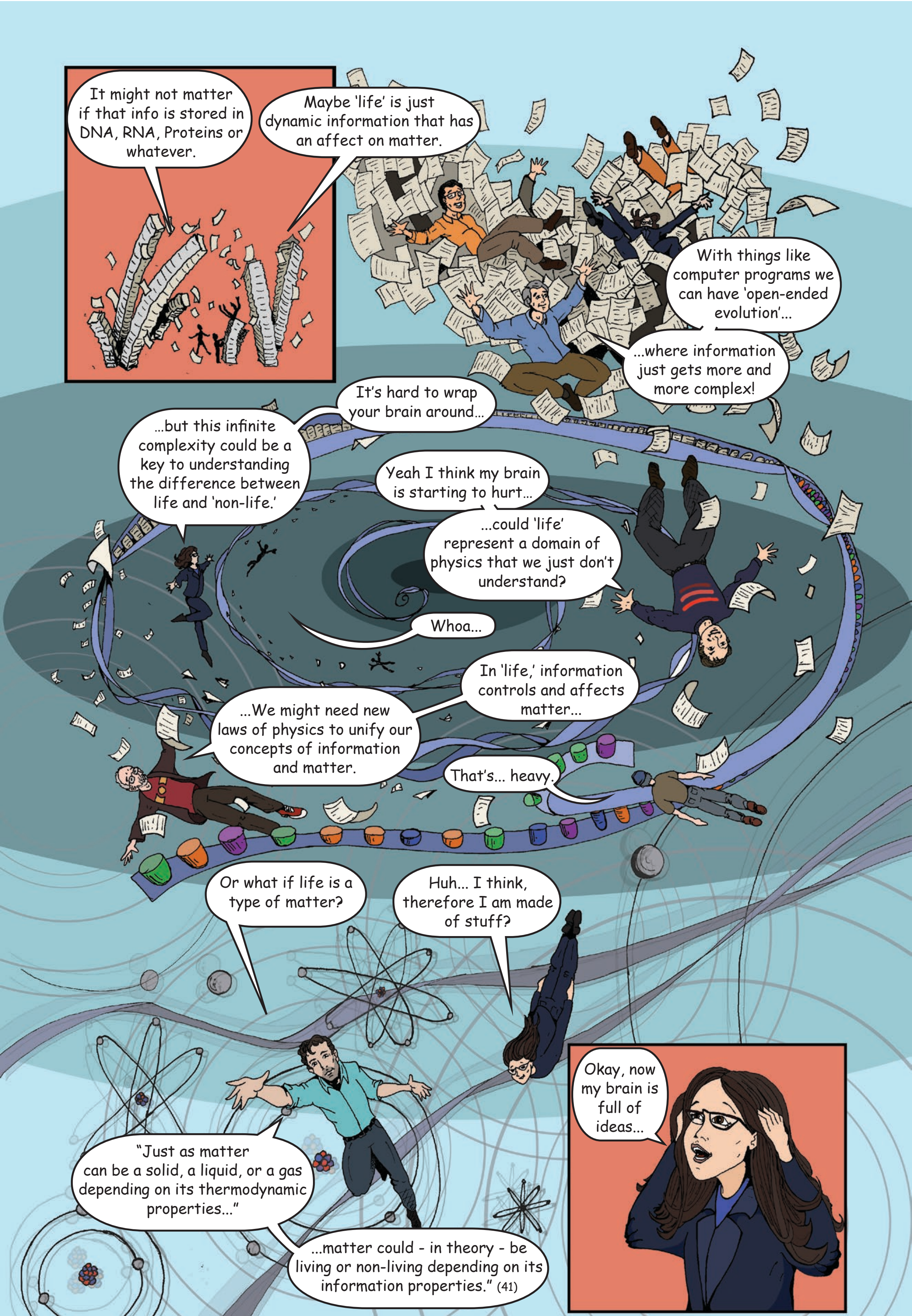

Large groups of chemicals could have been similar to the swarming behaviour of some birds.
What do you mean?
When a flock reaches a critical number, individuals no longer control the behaviour of the group, but instead begin acting as a single entity.
Or like Wikipedia? (40)
What does Wikipedia know about the origin of life?
Simon DeDeo, Santa Fe Institute
It has to do with the interaction between human minds and society.

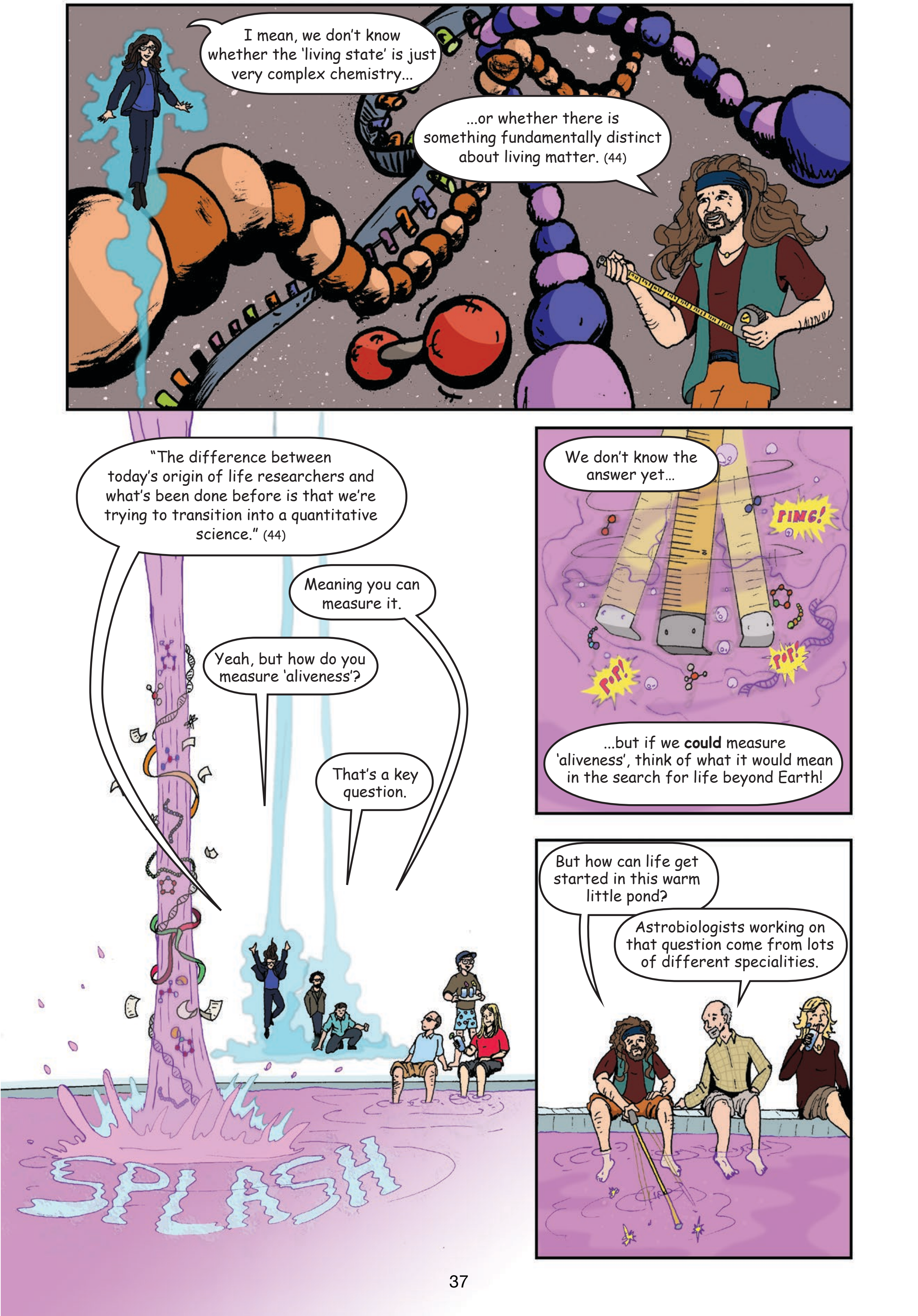


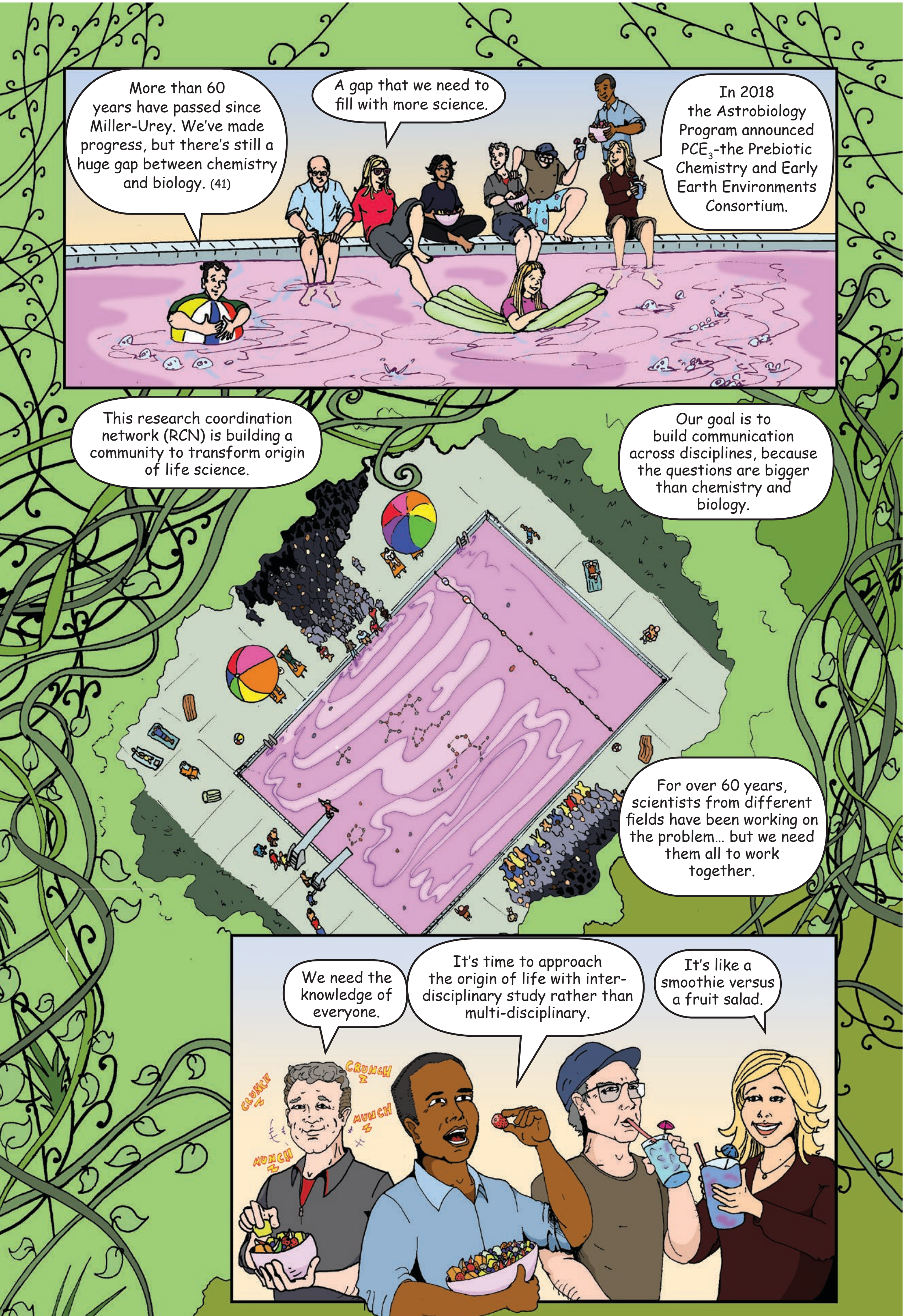
You can't predict how individuals will behave. But, predictable patterns of competition and cooperation do emerge.
Maybe this is what the origin of life looked like... unpredictable behaviours at the level of each molecule, but patterns of interaction at higher levels.
That makes sense...
So now we're looking past the little pieces that make up a living cell.
There is value in figuring out how certain molecules were made and evolved, but that doesn't solve the core questions. (41)
George Cody (Carnegie)
Maybe there are bigger, more general principles that can help us understand how life originated.
In 2014, a grass roots movement called 'Modeling the Origins of Life,' or MOL, took hold...

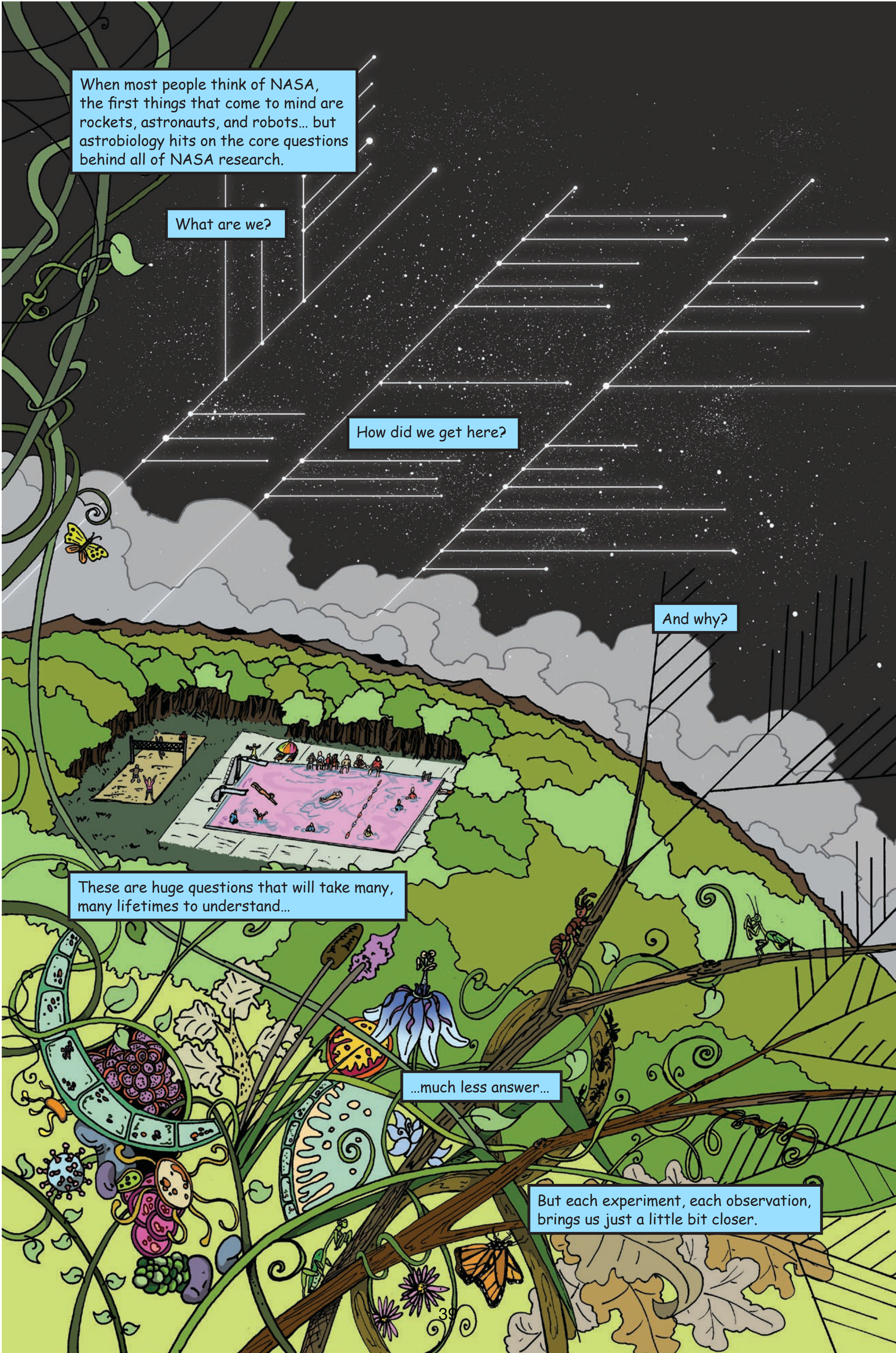

In 2012 the Japanese government committed to building an institution to tackle the fundamental questions of life...
Meetings were held in the United States and Japan. (41)
...the Earth-Life Science Institute (ELSI) at the Tokyo Institute of Technology.
Tokyo, August 2015
Kyoko Akiyama, ELSI
Then came the ELSI Origins Network (EON), which expanded partnerships in origins research around the world.
Hanako Ricciardi, ELSI
Around 40 scholars gathered at Tokyo Tech for the first EON meeting.
The participants began to peice together a strategy to encourage fresh approaches to studying life's origins. (42)
Part of this strategy was to bring in scientists who study artificial life, or synthetic biology.
Christine Houser, ELSI
Okay, so far we've talked about a historical approach to the question.
We're trying to find evidence to reconstruct the events that led to life on Earth.
We look for evidence in the geological record, or biochemistry, and so on.
But synthetic approaches don't necessarily care how life started on Earth...
It's more about how to create life now in the lab, or even virtually.
Chris Adami (Michigan State)

Studies like computational astrobiology provide another approach to the origin of life problem.
We're not so much focused on life on Earth.
We're more concerned with the idea of life as a Universal phenomenon.
Which we can study with things like computer software.
Synthetic biology has a long history as well...
...and can be traced back to the work of John Butler Burke. (43)
I made a 'Radiobe!' It's half microbe, half radium!
1905
Information aspects of life could be independent of chemistry and biology.
WHIRRR
In some ways, life is just information that can copy itself.
And information, particularly dynamic or changeable information, is a key property of life.
Computational approaches which match real chemistry give us working models for life's start on Earth, and also its potential on other worlds.
Bruce Damer, UC Santa Cruz
Paul Davies, Arizona State
DNA holds information, which is copied (and altered) as organisms reproduce.
We use 'artificial life' programs to explore the rules behind how information is passed down.
In fact, that might be THE key property.
The concept of information is key to understanding life in the Universe. (41)


It might not matter if that info is stored in DNA, RNA, Proteins or whatever.
Maybe 'life' is just dynamic information that has an affect on matter.
With things like computer programs we can have 'open-ended evolution'...
...where information just gets more and more complex!
It's hard to wrap your brain around...
...but this infinite complexity could be a key to understanding the difference between life and 'non-life.'
Yeah I think my brain is starting to hurt...
...could 'life' represent a domain of physics that we just don't understand?
Whoa...
In 'life,' information controls and affects matter...
...We might need new laws of physics to unify our concepts of information and matter.
That's... heavy.
Or what if life is a type of matter?
Huh... I think, therefore I am made of stuff?
"Just as matter can be a solid, a liquid, or a gas depending on its thermodynamic properties..."
...matter could - in theory - be living or non-living depending on its information properties." (41)
Okay, now my brain is full of ideas...


I mean, we don't know whether the 'living state' is just very complex chemistry...
...or whether there is something fundamentally distinct about living matter. (44)
"The difference between today's origin of life researchers and what's been done before is that we're trying to transition into a quantitative science." (44)
Meaning you can measure it.
Yeah, but how do you measure 'aliveness'?
That's a key question.
SPLASH
We don't know the answer yet...
PING!
POP!
POP!
...but if we **could** measure 'aliveness', think of what it would mean in the search for life beyond Earth!
But how can life get started in this warm little pond?
Astrobiologists working on that question come from lots of different specialities.


More than 60 years have passed since Miller-Urey. We've made progress, but there's still a huge gap between chemistry and biology. (41)
A gap that we need to fill with more science.
In 2018 the Astrobiology Program announced PCE_3-the Prebiotic Chemistry and Early Earth Environments Consortium.
This research coordination network (RCN) is building a community to transform origin of life science.
Our goal is to build communication across disciplines, because the questions are bigger than chemistry and biology.
For over 60 years, scientists from different fields have been working on the problem... but we need them all to work together.
We need the knowledge of everyone.
It's time to approach the origin of life with inter-disciplinary study rather than multi-disciplinary.
It's like a smoothie versus a fruit salad.
CRUNCH
CRUNCH
MUNCH
MUNCH


When most people think of NASA, the first things that come to mind are rockets, astronauts, and robots… but astrobiology hits on the core questions behind all of NASA research.
What are we?
How did we get here?
And why?
These are huge questions that will take many, many lifetimes to understand…
…much less answer…
But each experiment, each observation, brings us just a little bit closer.

Further Resources and References cited in this issue:

1. Domagal-Goldman, SD, Wright, KE, et. al. (2016) The Astrobiology Primer v2.0. Astrobiology, Vol. 16, No. 8.
2. Service, RF (2015) Researchers may have solved origin-of-life conundrum. Science. doi:10.1126/science.aab0325
3. Miller, S. (1953) A Production of Amino Acids under Possible Primitive Earth Conditions. Science, Vol 117(3046), 528-529.
4. Lazcano, A, Bada, JL. (2003) The 1953 Stanley L. Miller experiment: fifty years of prebiotic organic chemistry. Origin of Life and Evolution of the Biosphere, Vol. 33, No. 3, 235-242.
5. Lazcano, A. (2010) Historical Development of Origins Research. Cold Spring Harbor Perspectives in Biology, Vol 2, No 11.
6. Schwartz, M. (2001) The life and works of Louis Pasteur. Journal of Applied Microbiology, Vol 91, No 4, 597–601
7. Peretó, J, et. al. (2009) Charles Darwin and the Origin of Life. Origin if Life and Evolution of the Biosphere, Vol 39, No 5, 395–406.
8. Oparin, AI. (1924) Proiskhozhedenie zhizni. Moscow: Mosckovskii Rabochii (reprinted and translated in Bernal JD, the origin of life. London: Weidenfeld and Nicolson, 1967)
9. Haldane, J.B.S. (1929) Origin of Life. The Rationalist Annual, Vol 148, 3-10.
10. Delaye, L, Lazcano, A. (2005) Prebiological evolution and the physics of the origin of life. Physics of Life Reviews, Vol 2, 47–64.
11. Schrodinger, E. (1944) What is Life? The Physical Aspect of the Living Cell. Cambridge University Press, 194pp.
12. Oparin, AI, Fesenkov, VG. (1961) Life in the Universe. New York, Twayne Publishers.
13. Astrobiology Magazine (2003) Life's Working Definition: Does it Work? Astrobiology Magazine. Available at: https://www.astrobio.net/origin-and-evolution-of-life/lifes-working-definition/
14. Gaucher, EA, et. al. (2010) Deep Phylogeny—How a Tree Can Help Characterize Early Life on Earth. Cold Springs Harbor Perspectives in Biology, 2:a002238
15. Cooper, K. (2017) Looking for LUCA, the Last Universal Common Ancestor. Available at: https://astrobiology.nasa.gov/news/looking-for-luca-the-last-universal-common-ancestor/
16. Woese, C. (1998) The Universal Ancestor. Proceedings of the National Academy of Sciences of the United States of America (PNAS), Vol 95(12), 6854-6859.
17. Glansdorff, N. et al. (2008) The Last Universal Common Ancestor: emergence, constitution and genetic legacy of an elusive forerunner. Biology Direct, Vol. 3(29), DOI: 10.1186/1745-6150-3-29
18. Cech, T. R. et al. (1981) In vitro splicing of the ribosomal RNA precursor of Tetrahymena: involvement of a guanosine nucleotide in the excision of the intervening sequence. Cell 27, 487–496.
19. Zaug, AJ and Cech, TR (1980) In vitro splicing of the ribosomal RNA precursor in nuclei of Tetrahymena. Cell 19, 331–338.
20. Kruger, K, et al. (1982) Self-splicing RNA: autoexcision and autocyclization of the ribosomal RNA intervening sequence of Tetrahymena. Cell, Vol 31(1), 147-157.

21. Szostak, JW (2012) The eightfold path to non-enzymatic RNA replication. Journal of Systems Chemistry, Vol. 3. DOI:10.1186/1759-2208-3-2.
22. Doherty, EA and Doudna, JA (2001) Ribozyme structures and mechanisms. Annual Reviews of Biophysics and Biomolecular Structure, Vol. 30, 457– 475.
23. Lilley, DMJ (2003) The origins of RNA catalysis in ribozymes. Trends in Biochemical Science, Vol. 28, 495–501.
24. Cleaves, HJ, et. al. (2012) Mineral-organic interfacial processes: potential roles in the origins of life. Chemical Society Reviews, 41(16), 5502-5525.
25. Rode, BM (1999) Peptides and the origin of life 1. Peptides, Vol. 20, 773–786.
26. Cairns-Smith, AG and Hartman, H, editors (1986) Clay Minerals and the Origin of Life, Cambridge University Press, Cambridge, UK.
27. Brack, A (2006) Chapter 7.4: Clay Minerals and the Origin of Life. Developments in Clay Science, Vol 1, 379-391.
28. Cech, TR (1989) Exploring the New RNA World. The Nobel Prize, available at: https://www.nobelprize.org/nobel_prizes/chemistry/laureates/1989/cech-article.html
29. Petrov, AS, et. al. (2014) Evolution of the ribosome at atomic resolution. PNAS, Vol. 111(28), 10251-10256.
30. Bray, MS, et. al. (2018) Multiple prebiotic metal mediate translation. PNAS, Vol 115(48), 12164-12169.
31. Kacar, B, et. al. (2017) Constraining the timing of the Great Oxidation Event within the RubisCO phylogenetic tree. Geobiology, Vol 15(5), doi: 10.1111/gbi.12243
32. Kacar, B, et. al. (2017) Resurrecting ancestral genes in bacteria to interpret an cient biosignatures. Philosophical Transactions of the Royal Society A, 375(2109).
33. Garcia, AK, and Kacar, B (2019) How to resurrect ancestral proteins as proxies for ancient biogeochemistry. Free Radical Biology and Medicine, doi: 10.1016/j.freeradbiomed.2019.03.033
34. Deamer, D (2006) The Role of Lipid Membranes in Life's Origin. Life, 7(1). 5.
35. Chen, IA, Walde, P (2010) From self-assembled vesicles to protocells. Cold Spring Harb Perspect Biol, 2(7). doi: 10.1101/cshperspect.a002170
36. Chen, IA and Szostak JW (2004) A kinetic study of the growth of fatty acid vesicles. Biophysics Journal, 87(2). 988-999.
37. Strecker, A (1850) Ueber die künstliche Bildung der Milchsäure und einen neuen, dem Glycocoll homologen Körper. Annalen der Chemie und Pharmacie, 75 (1). 27-45.
38. Szostak, JW (2009) Origins of life: Systems chemistry on early Earth. Nature, 459(7244). 171-172.
39. Krishnamurthy, R (2017) Giving Rise to Life: Transition from Prebiotic Chemistry to Protobiology. Accounts of Chemical Research, 50(3). 455-459.
40. https://www.wikipedia.org/
41. Bontemps, J (2016) Seeking New Insight into Life's Origin. Available at: https://astrobiology.nasa.gov/news/seeking-new-insight-into-lifes-origin/
42. Scharf, C (2016) A Strategy for Origins of Life Research. Available at: https://astrobiology.nasa.gov/news/a-strategy-for-origins-of-life-research/
43. Campos, LA (2015) Radium and the Secret of Life. University of Chicago Press. 352 pp
44. Walker, SI and Davies, P (2013) The algorithmic origins of life. Journal of the Royal Society Interface, 10(79). doi: 10.1098/rsif.2012.0869

NP-2015-04-1737-HQ