Q: **Ngai pirrku mankulankula. Ngai nari Kumatpi Marrutya. Ngai wangkanthi marni naa pudni. Kaurna yarta- ana. Irdi yarta. Hello, it's Micky O'Brien here. Ambassador of the Kaurna people. And today where I'm going to country. And I'm known as the impatient one. So Ngadlu wangkanthi. Naa marni naalitya. Marni naa pudni parrku pirrku. Warra mankunthi. Kaurna yarta. So we can hello to you. And we also welcome you to this podcast recorded on Kaurna country.**

Q1: **Welcome to the South Australian Museum podcast. I'm your host, Meg Lloyd, and this week we'll be revisiting a lecture from 2018. Animal life is remarkable in its diversity. Particularly in the variety of shapes and sizes we see around us today. And in some ways even more remarkably in those life forms that have long gone extinct. How does this variation come about? And is it limited in its possibilities or infinite? Doctor Emma Sherratt is an Australian Research Council Future Fellow. She is a world expert in the analysis of animal form and evolution. Her research spans animals big and small, from sea snakes to scallops, frogs to fossil lizards, and mammals to cuckoo eggs. She is currently an honorary researcher at the South Australian Museum and holds two grants. An ARC Fellowship on morphological evolution of invasive rabbits and hares of Australia, and an ARC discovery project with Flinders Uni and SAM Researchers, Mike Lee and Alessandro Palci, on snake fangs, insights into evolution, paleo climate, and bio design. In 2018 Emma was invited to share her work on morphology, the study of animal forms, for our Sprig Lecture Series. She explains these concepts through beautiful description of an imaginary museum in her lecture, the shape of life and the museum of possible forms. You can find Emma's work at her website, emmasherratt.com.**

P1: Let's go with this. Oh, there we go, I am live. Sorry for that technical difficulty. Thank you very much for that extremely kind introduction. And thank you everybody for being here. It is an absolute pleasure and an honour to talk to you this evening. Particularly in this gallery. I have a British accent, as you can tell, but I wasn't born in England. I became British through the fact that my dad is British. I was born in the Pacific. I was born on Bougainville Island, which was Papua New Guinea but is now the autonomous region of Bougainville. And there's a lot of things around me this evening that are really fond memories of my childhood. And that includes, you know, spears and stuff. And I think Bougainville Island really was the very beginnings of my love of the natural world. I have seen snakes and lizards, particularly my favourite animals, that probably scientists have never even seen. And I probably poked them as a child. And on top of that, the other thing that I think really that made me who I am was seeing such diverse people and diverse cultures, and diverse body modifications. So my love of jewellery definitely came from Papua New Guinea very early on. So today I would like to talk to you not about those things but about my research. Why I do what I do. And hopefully you'll get a sense of why it's important. And in fact why it's so intuitive that you're probably doing it on a daily basis. So let me get started. In the obligatory biodiversity slide. So I'm an evolutionary biologist by training. And I'm interested in understanding how the diversity of life that we see around us came about. I spend my days studying the ways that animals look. And so I'm very drawn to images like this, which show off the 35 or so animal phyla that exist on this planet. The phyla being probably the largest classification, the broadest classification of all the animals. Sorry to the people who are interested in plants here, but I won't be talking about any of those this evening. My thoughts are always to the animal kingdom. And this slide really drives home the amazing diversity of how animals look. That there's so many different kinds, even though in fact quite a lot of them have all converged on the same type which is to look a lot like a worm. There are in fact many different kinds of worms, and to simply call something a worm is really not to do it justice. So from bees to birds, and worms to whales, from sea cucumbers to sea snakes it's a striking world out there. And perhaps can be a little bit even daunting to say, well where do we even start when we want to study what we can see. The thing that I want you to take home from this is that they are diverse and it is particularly the way that they look, their morphology, a word that I will use a lot this evening, that I spend every day studying. Morphology is analogous to anatomy. And so that's how I want you to think about the word this evening if you've never heard of it. Now the particular aspect of morphology that I'm most excited about is the skeleton. Now this might be the internal skeleton, like we have as vertebrates, and we share with the snakes and the fish, and the turtles. But it could also be an external skeleton like you see in the molluscs. Here I pictured a scallop up in the top. The skeleton is interesting and exciting because long after the animal has died it's the skeleton that is left behind and fossilised. And so understanding the way that the skeleton looks in our modern animals can help us infer what has happened in the past when all we have left are their bones. Something I won't talk to you too much about this evening, but I have had a little of a dabble in palaeontology. Even though it's not really my world. And that is that that skeleton right on the far right was in fact a lizard encased in 25 million year old amber. And that was the first project that I did out of my PhD and it got me on this route to where I am today. But before I go any further in talking about my research what I think is really important is knowing as well who stands in front of you. For the young members of the audience you might be wondering how do you come to be in a job like this where I get to stare at animals all day long and be paid for it. Well it turns out that I never wanted to be an evolutionary biologist. That wasn't my burning dream as a child. First of all I wanted to be a train driver. And then I was desperately interested in dentistry. I had got braces at the age of 11 and I was fascinated, absolutely mesmerised by the cast that the dentist had made of my mouth. And with some calculations, and planning of the trajectory she was able to straighten my teeth to what I have today, which is pretty good. And so I wanted to be an orthodontist. And I was hell bent driven to do that. And I spent all of my teenage years focused on dentistry. And then I didn't get the grades to get into dentistry. So what do you do? Well I came and backpacked Australia like most British people do. And I worked at a couple of wildlife sanctuaries because I did really like animals, I just didn't think there was a job in it. And I worked in these wildlife sanctuaries. And the people that I met showed me that there was this thing called zoology. Now that doesn't just mean you work in a zoo. It means that you're literally just interested in animals. And so I came back to the University of Manchester where I had been accepted on a biology degree, because they were going to let me in, just not for dentistry. And I came back and said I want to be a zoologist. And that's where I started. So I have a long interest in anatomy and functional morphology. But another important things was to realise that this is a very old science. People have been interested in the way that animals look for centuries. For decades. Yet it's losing favour because DNA tells us so very much. Some people might think that anatomy has kind of disappeared. And so what I needed to do was to bring comparative anatomy into very much the 21st century. And so during my undergraduate degree I got to go to the Natural History Museum in London to work for a year. And that is where I became trained as a comparative anatomist. And visualisations like this are just stunning to me because – I get goosepimples looking at them, because it's extraordinary. Comparative anatomy is so fundamental to everything that we see around us, that we all share as vertebrates very much the same skeleton. It's just small modifications on that skeleton that gives us the diversity of vertebrates. And so tonight I'd like to talk to you about this, and how I've come to do this kind of work. But as I said I had to make it more 21st century, and so I had to go from a descriptive world of comparative anatomy where we simply said this bone is longer than this bone, and these bones fit together in this particular way, into something that was rigorous, quantitative, much more objective and robust. And that is where I discovered the world of morphometrics. Now I'm not a mathematician but I am heavily driven by maths, and if anyone saw the Q&A program last night we have a dialogue in Australia right now that it is extremely important for everybody to have an understanding of maths. And hopefully this evening you will also see why it is so important to have a good understanding of maths, because maths underlies all of the biology that we have around us. So as my talk says, my slides title slide says, I'm going to talk to you about the shape of life. And this is a field where we use diverse measurement tools, a variety of different types from highly technological down to a ruler, in order to be able to measure, quantify, analyse and disseminate information to everybody around us. I'll just take a quick swig. And then I'd like you to tell me what this is.

P2: A mirage?

P1: It does look like a mirage, doesn't it. What building is this?

[Indistinct – Overtalking]

P1: Adelaide Oval. Absolutely. Correct. So yes, it's the Adelaide Oval. You recognise this. But how did you determine that it was the Oval?

P2: The shape of the arch.

P1: The shape of the arch. Absolutely. It is such a distinctive shape. Now the position – so the orientation of the image didn't seem to bother you with that shape information did it? You were still able to recognise it even though it was upside down. And so this tells us then that orientation, rotation, doesn't mean shape. That's not a particularly important part of shape because you can still deduce shape even when something is rotated on an oblique angle. Another important point is that you're able to recognise its shape despite the fact that the image is only a metre and a half tall, and the building itself is pretty enormous. So size is not shape. Size does not make shape itself. Thirdly we're here. Whereas the Adelaide Oval is about a kilometre over in, ooh, probably that direction just there. So the position of the object doesn't get in your way of recognising shape. All of these things are perfectly logical to you, yes. So now what you have just done is you have just defined shape in a mathematical way. Shape is everything that is left once you've removed rotational variation, translational variation, the position in space, and size variation. That's shape. Now size is important because size influences shape. But size and shape are two separate entities. And together they produce something called form. So I want you to remember those terms this evening because there are distinctions and I will be using them as such. Now another example of how we do shape analysis on a daily basis is in picking out particular features. So how did you know that the Oval was the Oval? Well you mentioned one particular feature, the round arch. So oftentimes we actually just pick out particular features in order to describe the shape of something. These caricatures by Leonardo Di Vinci show this off. That we know that the people wouldn't have really looked like this, they're probably mega exaggerations, but they show off the features that if you saw this person walking in the street you would know instantly that that's them. And so our shape analysis and our intuitive way of studying the way that things look, we do on a daily basis, and we do through exactly the same means by which I do. In the world of morphometrics we have just refined this and formalised it, and bring it into the scientific world. But I want you to realise tonight that you are all doing shape analysis on a daily basis, really every time you open your eyes. And I think an important one in terms of recognising people is that we do focus on things like features, big noses, coloured hair, glasses. If someone cuts their hair or takes off their glasses it can be a moment to recognise that that is in fact the person that you knew before. And that is because we don't use all of the information often when we are distinguishing shape. And so morphometrics simply does exactly the same thing, what we're interesting in picking up the important key features that tell us the differences between species, the differences between groups, and how we can identify them. We're going to do another interactive thought experiment. The other part of my title is called the Museum of Possible Forms. This is an absolutely stunning display at the Berlin Natural History Museum. They were unfortunately heavily damaged during World War II, but it did mean that they were able to build beautiful new facilities when they did. And this displays perfectly what I would like for you to do next. So imagine a room in a museum that looks like this. Okay. It's got three dimensions. Now imagine that in that room we have all mammals that have ever existed. We're going to have to arrange them in that room in some way in order to be able to find them. So first of all let's arrange them from left to right by how big they are. We'll put our elephants and our blue whales over on the left. And we'll put our mice over on the right. Okay, bear with me, fantasy room, it's going to have to be pretty large to be able to do this. How's about next we say, well the next important feature is how long the legs are. So from top to bottom we'll have all the animals that have really short legs arranged down the bottom of this room. And we'll have all the animals with really long legs up at the top. So we've got our giraffes up there, and we've got our stoats and our weasels down at the bottom. Now stretching out as far to the back of the room as we can we've got the robustness of the body. So we'll have all of the slender animals at one end. And we'll have all of the rotund animals at the back. Have you visualised this room? Can you see it? Now as we walk through this room, this museum of possible forms, we're going to see some shelves are overflowing with animals. There's so many of them they can't fit on the shelf. That's probably going to be where you've got your bats, and you've got your mice and rats. You've probably also got a lot of monkeys in there too. But there are other areas of this room that are completely empty. Turns out we can't have a mammal that has no legs at all, like we have a snake, that it's not possible to have a completely legless mammal. This is because of its physiology. There's a variety of reasons why that exists. And so the shelf that would have the legless mammal simply is empty. And in fact there's a lot of areas in this room that are completely empty because those animals have died out. That they no longer exist on this planet. Now what you've visualised is actually something that we use in morphometrics called the morpho space. That three dimensional space that you're imagining, where you could walk down every shelf and every corridor, is these mathematical spaces that we create in order to start asking questions about evolution and how the animals that we see about us came about. So at this point we have the idea about morphology. We have an idea about diversity. We should probably start thinking about how we're actually going to capture this diversity. My descriptions of long legs and short legs, and rotund bodies, and big bodies and small bodies is just not going to be sufficient. Because what I say to you is big might not in fact be big to you at all. You'll be like, no, no, this thing is big. So we need to use mathematical descriptors rather than words. Because sometimes words simply don't work for us. And so when I started to talk about measurements you probably thought about getting your ruler out and starting to take some linear measurements of things. So here are some limb bones of a variety of mammals. This is the femur from a set of very well known animals. And we can see that if we took just two linear measurements, a length and a width, at the same precise point on each one we'd be able to get some information about how the shape changes as they are getting bigger. The dogs ones are basically long and thin, and the cow is a lot more robust. And if you've ever seen an elephant one it is truly enormous and very large because of course a large animal needs a large surface area to be walking on. So linear measurements are very useful for us to be able to capture a lot of things. But it doesn't always work. Here are two drawings of two different skulls, rodent skulls. They have different shapes. Your eyes can easily see that there are subtle differences, particularly in the cheek bones. So we're looking at the top few here. We can take some linear measurements in the same way that we just did on the long bones. And we can see that in fact they capture what we think are the differences, but when we bring those measurements together we realise that the two skulls have exactly the same dimensions. That these linear measurements are precisely the same size. So in fact the linear measurements didn't tell us anything about the shape differences that we can so clearly see with our eyes. And this was definitely a problem for a long time in biology. Until the world of geometric morphometrics came about. And that was simply to say well, you know what, let's just look at the end points of those linear measurements. So if we think about the end points of those linear measurements, rather than the lines themselves, we now have a star configuration, where we're using the X and Y coordinates, just like the

Cartesian coordinates of a map. We're using the coordinates as our measurements rather than the linear measurements. In this way we can put on a whole load more and we don't have to arbitrarily decide on linear distances, we simply have to put all these points on, and then when we bring them together we can clearly see where the shape difference lies. We overlay them. We superimpose them once we've removed what we said earlier, the size, the rotation and the translation. We bring them together and now we can clearly see the zygomatic arch, that cheekbone is differing. And this was a very powerful breakthrough for morphometrics and the world of comparative anatomy. Because now there were so many more very complex objects that we could measure. And this is what I've spent the last 10 years in perfecting. But sometimes landmarks and linear measurements don't work in the slightest. Sometimes you're faced with something as curved as an egg, and you think, oh dear, what am I going to do with this now? Well it turns out that mathematics doesn't have a problem with this in the slightest. Mathematics have been thinking about curves for a very long time, and they think about it in terms of waves. So Fourier analysis, which is the same as the wavelet analysis for speech when you look at soundwaves. It's exactly the same analysis, and what we do is we fit first of all the first harmonic, the first curve. And that is here, a nice circle, as K1. A red circle. Then we go, well that doesn't really fit the shape. So we put on another harmonic. And we put on another harmonic until we eventually approximate the shape. And for round things like eggs this works remarkably well. But interestingly enough I was very fortunate to come across this paper, which is by a biologist, Dan Chitwood, is in fact a tomato biologist. He works on the genetics of tomatoes in the US. But he also has a penchant for – ooh, that's a real shame, what happened there? Oh, well, sorry. He has a real interest in violins. So he used exactly the same approach that he would normally use on leaves of tomatoes to measure the shape of violins. And it's a really exciting paper because it turns out that there's a whole load of differences in shapes of violins, but over time they've converged pretty much on the same shape. That all of the violin makers over time have converged their shape to follow Stradivari, and the original sort of masters of violin making. It has nothing to do with the sound from what I know of the paper. It's simply that it looks appealing and so they all copy that. And so these exact same techniques that we use on a daily basis in our lab are actually being used all over the place for all sorts of exciting questions. Another glass of water. I apologise for the fact that that is a Mac to PC issue. Turns out that it still happens after all these years. But let's go back to the biology because that's what we're really here for. So tonight I'm going to talk to you about just three stories of my research that has used these methods to try and understand the shape of life and the museum of possible forms. And for each one I'm going to acknowledge the people that I've worked with because most of the time they are the experts on the organisms themselves. And I'm just coming along as the shape analysis expert. And so if I make any mistakes these are entirely my own and please don't flog my co-authors for my mistakes. This first research is looking at cuckoo eggs. So coming to the egg problem. And my colleagues, Marie and Iliana and Naomi, came to me and said, we have a really exciting problem which we think you can help us with. We've got mimicry. You've heard of mimicry? You've heard of the fact that cuckoos are a bird that parasitise other birds. They lay their eggs in other birds' nests. Years of researchers have looked into whether or not the eggs look similar to the host's eggs. And in this case you can clearly see there is an odd one out. There is a pretty large egg sitting in this nest of other eggs. But it has quite a similar colour. So previous research had showed that eggs often are visually similar in terms of the colours and the patterns. Sometimes there's size similarity, but not always. But no one had really looked at shape. And so we used the CSIRO collections and we decided to do a small study of three Australian species of cuckoo that have very interesting nesting behaviours. So the fantailed cuckoo will always parasitise a nest that is closed. So one of these little – I would say a closed nest, I'm trying to think of the other term, I apologise. Hmm?

P2: Dome.

P1: Dome. Thank you. The domed nests. So once it's got in there it lays its egg, but it's nice and dark. The Pallid Cuckoo on the other hand will always parasitise a nest that is open. And the Brush Cuckoo doesn't really matter. It likes to do both. So some species that it parasitises are dome nesters, and some are open nesters. So it's a nice little experiment of animals that are not so closely related, but are doing a similar thing, and this allows us a statistical comparison between whether or not there is shape similarity between that of the cuckoo egg and the host's egg. To do this we take a lot of photographs of eggs. With a scale bar, most importantly, because size is important to us. And then we simply extract the outline of the egg and use those mathematical techniques that were used on the violin in order to extract the shape of the egg. So we've got a very faint outline here. Apologies for that. That is a single egg. Then all of the eggs put together. So we can see that there's some variation, which is nice. This is also the case for any eggs that you buy in the supermarket. Pull them all out later. Have a look at them. They will be different to each other. And the results were striking, but perhaps not what we were expecting. So it turns out – so on the Y axis we have shape difference, so basically how similar the cuckoo egg is to the host's egg. If it's down at the bottom, around about zero, the eggs are basically identical in shape. And if it's up at the top the eggs are not similar in shape at all. And that's demonstrated by the grey shadow that you can see there. Now it turns out that the amount of similarity in cuckoo eggs to their host eggs entirely depends on the nest. That in fact in open nests, where you can see the egg, they are extremely similar. It's not perfect similarity but it's enough of a shape similarity to obviously confuse the host. But in closed nests, where you don't see the egg, there's no similarity at all. And this actually goes to the theory that exists in cuckoo research already, which is that you only have the selective pressures to look similar, to have that kind of mimicry if in fact there is a chance it's going to be pushed out. And in a closed nest they simply can't see it. But the size information is the exact opposite. That there is in fact extremely strong size similarities in the closed nests. Which is likely to do with the fact that there is selection pressure for the mother of the host nest to come in and go, well this doesn't feel right. This feels substantially larger than my eggs. So this is the kind of information that we can get from using these techniques in a rather simple and quick approach using also eggs that have been sitting in the CSIRO collections for a long time. You might know the stories by Rudyard Kipling. I was certainly told them when I was a child. The Just So stories of how the elephant got its trunk. And how the rhino got it's really wrinkly skin. And you might think, you know, with these kind of stories that I'm telling you are just the Just So stories. And in some ways it is but we need to be more rigorous than simply deciding that something has a feature that seems to fit its environment and therefore it must be an adaptation. And so for this we need to take a much more rigorous approach. And usually what we do in evolutionary biology is to use the tree of life to create the experiment for us. So if two animals share a similar feature that looks to be useful for its environment, let's say we've got two hummingbirds and it has a long beak, and you see them working on very long flowers, we can think, oh well, that seems to be useful. The long beak seems to be able to get to the bottom of the flower. But if those two hummingbirds are closely related it could simply be that the ancestor of those hummingbirds also had a long beak. And therefore it's not an adaptation it just simply is how these species were born. And so what we need to do is to go much broader. We need to take species that are not related to each other. And when we see that they share similarities, and they live in similar environments, that's when we start to think, you know what, this is probably an adaptation. A lot of this work is still correlative. It's not causative. We're not saying that it absolutely is the case, but what we see is decent evidence to back it up. So I just wanted to point that out in case there was anyone beginning to feel a little bit sceptical that all I was doing this evening was going to be making Just So stories. So Steve pointed out that I spend all my time working on snakes nowadays. And they do occupy a lot of my time. And you may have seen in the news recently that the sea snakes have just got a bit of a bad press. That was the first fatality in Australia from a sea snake bite. But it is important to know that they are venomous. And that they should be treated simply with caution. Sea snakes are loving creatures. They will come up to you and look at you through your mask when you're snorkelling, or you're scuba diving. They aren't aggressive animals. They aren't going to go for you. And so I just want you to bear that one in mind if you see any sort of negative information in the press at the moment. So this work was done here at the University of Adelaide, with my collaborators, Kate Sanders and Arne Rasmussen in Denmark, and they really are the sea snake experts. And they came to me – and it was a similar story – Emma, we have a very exciting system here. And we need your help. We think that there's something very strange going on with the morphology of these animals. And as soon as I'm shown the picture of a cool looking creature I'm right in there. I have to start studying it. Now the sea snakes, to give you a little bit of background, they are the true sea snake. So you may have heard of things like sea crates. Sea crates can come onto land. They lay eggs. They're fairly good at moving on land. The sea snakes are just blobs on land. For the most part they're really not good at moving around. They don't come onto land unless they've really been beached, or there was a great picture of an eagle that probably dropped one on a road up in the Northern Territory. They give birth to live young. So they spend their entire life in the ocean. And they are extremely good water dwelling animals. They are related to the tiger snake, and to the brown snake, so they have a very similar venom. They are highly venomous. Their fangs are at the front of their mouth. It isn't true that their fangs are too small to be able to bite through your wetsuit. But for the most part they're just not simply going to go at you. Now they probably came around about 6 to 16 million years ago. It's quite difficult to get a very accurate thing on this because unfortunately we don't have fossils of these animals. Anything that lives in the sea, it's difficult as to whether or not we're going to get fossils out of it. But you can see from the distribution that they have a wonderfully huge distribution centred around Australia. And that's why I wanted to talk to you about this. Because these are somewhat on your doorstep. Although I'm unsure about whether or not they're really coming into the Australian Bight.

Do I have a nod, or a shake? Just one. Thank you very much, James. Yes, so we've got a lot of species. They have entered the marine environment and then they've never come back. So they obviously must be loving it. Well in fact there's also great morphological diversity. Some of them are only half a metre long, and others are three metre long beasts. They are huge. And back in 1983 researchers noticed that some of them just look really strange. And they coined the term microcephalic for the curious narrow bodied sea snakes. They've got a narrow forebody. And in fact here the head. That is the head right there. So it has a tiny little head and a really fat body. And in fact there's a lot of them. There are 10 or so species at least that we know of that have this weird body shape. And you can see here compared to a regular looking sea snake that it really is dramatic. You've got this tiny little head right up at the top of the screen. And these big wide bodies. And flat tails. And the thought was, well, why? Why do they look like this? Is there anything that's happening in their environment, or can we tell a more scientific Just So story as to why the sea snake got its long, thin head. Well probably the most easy and most rewarding data collection I've ever done in my life was that I got to use some string. Truly. And I got to measure a load of sea snakes that we have here in the collection. We've got collections all over the world and we borrowed these sea snakes. And we took just two measurements. Because we thought, you know what, we can probably describe what is quite a complex morphology with just two simple measurements. We take the width behind the head and the width three quarters of the way down the body. This will tell us how wide the head is compared to how wide the body is. So taking some string. Then measuring the body length and getting some information from the literature about total body lengths. We start to think about the sea snake morphospace. So remember that room of our mammals and all of our different types of mammals. Well we're going to build up the sea snake morpho space. And we're simply using two measurements here. Because our eyes find it difficult to see that third dimension. And so it was easier to turn those two measurements on the body into a ratio and stick with length, and have a two dimensional space. So like looking in on a window display. And this is where all the species of sea snakes lie. So remember those empty shelves? Well it turns out there's a whole load of empty space where the sea snakes aren't. So if we look along the bottom we're talking about sea snakes that go from 50 centimetres all the way up to 3 metres. The little cartoons show you a short snake versus a long snake. And on the Y axis what we can see if a gradually thinning head and neck. Going all the way up to the top of this really quite ridiculous looking animal that has a hind girth that is three times larger than its head and its neck. And we see all of those sea snakes going up into the middle. So one thing that's quite striking is that all of the sea snakes that have this weird tiny little head are all about one and a half metres long. We don't know why. But that seems to be the optimal size. Pretty strongly so. So we've got the information. We've got the measurements. But is there anything that can tell us why this exits? Well huge amounts of dietary data was already collected, so we start to think about putting the diet information into this. And we had an inkling that it had something to do with burrowing animals. And burrowing. And putting the heads into things and crevices. So we put the proportion of burrowing prey onto this space and we immediately see something quite dramatic. Everything that has a short body, and has a really long thin neck, eats burrowing prey. Predominantly to 100 per cent of its entire diet is prey that lives in crevices and burrows. But there's one that sits on the far end. And we know that that is in fact a really huge species, it's a three metre long species, that also eats enormous burrowing eels. Huge crevice dwelling eels. So it's a large snake that takes really large prey. But other than that one, that kind of breaks away from our story, all of the others sit in this one space. But all burrowing prey isn't the same. We can't all paint it with the same brush. So we then start to think about the type of prey. And this is where the story gets really exciting. It turns out that everything that eats a goby, a burrowing goby, a crevice dwelling goby, which is a little fish, is just a small bodied animal. It has a small body. It's a small fish. And it just goes into those crevices and grabs it. But the ones that are eating actually quite large crevice eels, burrowing eels, like this one just here

– what are known as the snake eels in fact – they're all the ones with this weird shape. So strongly so that the environment has selected upon these animals to have this extremely strange morphology. And my research here at Adelaide is going to continue on this. It really is a watch this space. We're trying to understand how this comes about. We're looking at their internal skeleton in order to think whether or not it's something to do with the bones themselves. We're looking at the skulls. Using techniques like micro CT, which is basically X-ray imaging in three dimensions. We're using all of this technology to now try and understand this story better. It turns out it's ecology that's driving the pattern, but development must also be a part of it. Because it's the development of the animals that produces the morphology even if it's most useful for the ecology itself. So staying in the sea, but going to my third and final story for you this evening, are the scallops. This is work that I did at Iowa State University in the middle of the US, as far as I could possibly be on the east and the west from the sea. And that's what we used to use as the selling point actually for coming to Iowa. It was equally close to both coasts. There wasn't a lot there. And so that was the place that I became a programmer. That was the place where I started writing the software to do all this shape analysis. Because there wasn't a lot else other than corn and soy. That's what made the landscape so exciting. It was a different shape. You'd have the corn and then the soy. And then the corn – anyway, the scallops. I'm here to now persuade you, perhaps my most difficult persuasion of the evening, why you should care about molluscs. Here in Australia you're probably used to these ones. So of course you're thinking about the scallop as that nice little white morsel of yum that sits on your plate when you get a seafood platter. But next time have a look at the shell that it's sitting in. Because the shell is beautiful, and it's strange, and after tonight you're never going to look at it in the same way again. So over on the left you've got the commercial scallop, which has this flat top valve, and a very round bottom valve. And the way that you shuck it is to hold the rounded part and take your knife in right about at the oracle. And the oracles are those hinges that you see at the bottom of the scallop. But you may also have had the

Hervey Bay saucer scallop. I picked up a load of these shells when I got to eat them when I was at Hervey Bay recently. And they are just as tasty, but a completely different shell. Looking at it from the side you can see two beautifully smooth forms, and they are almost equally symmetrical, these shells. And then yet these animals are related to each other. They sit within the same group of being called scallops. Now you walk the beaches around here, of South Australia, and you're going to get to see these two. You're going to see the Queen Scallop and the Doughboy Scallop. And they are also beautifully shaped, but you're beginning probably to see some subtle differences. All of these scallops have subtly different shapes. And this has something to do with the life that they lead. Now, in Australia, you're wondering why am I talking about research that I did in Iowa in Australia. Well it turns out you have almost all of the world's types of scallops here in your oceans. And the only species of the Coral Scallop in the world is here in Australia in the Great Barrier Reef. Look at those beautiful red eyes. Those are eyes by the way. It's blue lips of sort, and then it has its eyes sitting on its lips. And it lives its life entirely settled inside sponges and corals. And that's why kind of doesn't look like a scallop. It's lost its oracles. It looks a lot more like an oyster. But it is quite definitely a scallop. And the thing that's really striking about all of these types that you've got is that they lie on a spectrum of mobility. Scallops have in fact got a much more exciting life than you're probably giving them credit for. Honestly. Now what you don't have in Australia sadly is the cementing species, there are only two of those in existence. One in the UK and the other one in North America. They cement themselves into the reefs and they stay there. And they sort of blend into the reef. So I should probably say scallops basically have a life cycle where they are tiny and they're free floating, and they come along and they attach to where they're going to be. And then they start to grow there. And most of the ones on the far left of this diagram spend their entire life attached to a single structure and stay there. And in fact you can see the baby scallop, which is right at the very base, at the bottom of the pointy part where the hinge is there's a tiny little curve, and that is the baby scallop. And the shell just forms in rings. So you can tell how hold it is by the number of rings. Just like a tree. So we go from the left to the right and we see all these different types of scallops. And the cementers and the nesters I've explained. And the Byssal attaching are the ones that sort of attach themselves a lot like a mussel. They spin a thread and that thread attaches to the rock. And then they just stay there attached to the rock all their life. They're filter feeders, so they don't really need to be going anywhere much. And yet weirdly enough some of them have started to move. The recessing scallops that we often eat, the ones with the very rounded bottom, spend their time actually buried under the sand. And they have a very flat top that allows them to bury under the sand, and let the sand sit level on top of their shells. Then you have some free living ones that just hang out on the top of the sand. They don't do much but they do swim. Like this. Like Pac Man. They clap their valves together and then they swim through the water. But they're not nearly as good as the gliders. The gliders, like our Hervey Bay Scallop, are the phenomenal swimmers. They will go for several metres at a time. And so you can see that that shiny smooth shell might have something to do with the fact that they're moving and that they need to be more hydrodynamic. Bring in some cool technology we capture shell shape using a 3D scanning, which is quite a lot similar to something called photogrammetry. Take lots of photographs of different angles and build it up. No, that is in fact not a shell. That was a picture I had to take from the internet of what I think might be a spaceship. But the technology that we have, in fact here at the South Australia Museum, can be used for all sorts of things. And here we took on an army of undergraduates to start building these beautiful shell models. And if any of you have a particular interest in scallops send me an email. I can send you some beautiful shell models. They're lovely. The model – ooh, we've got an update for you – not right now, thanks – this shell shape, these 3D models is exactly the same as the technology that you would use if you were to make animated cartoons. So you've seen all of your animated cartoons, the Minions are definitely my favourite, underlying their shape is this exact same structure. It is basically a set of interlocking triangles that can be coloured and smoothed and made to look three dimensional. So we build up a whole lot of these 3D models and it allows us to take very precise measurements. Because these are not creatures that are going to work simply in 2D with the outlines. And they're certainly not going to work with linear measurements. We need to cover them in landmarks. And so what we do is we create the geometry by simply throwing down what looks like a fishing net of points. Or imagine fishnet stockings. The intersections of fishnet stockings are the points of where you would put down a landmark. So they're equally spaced on here. The only ones that are put down to represent a functionally important and equivalent area are those numbered ones, one to five, which describes the hinge. But this technique allowed us for the first time, because no one had ever thought about the 3D – the how raised a scallop was – this was allowing us for the first time to get all of the dimensions and build up the scallop morpho space. So let's go to the scallop morpho space. Let's enter that room now. Because there's lots of measurements we have to boil them down with a wonderful mathematical technique called principle components analysis. I'm not going to bore you with that. But if you're interested send me an email. It means that we can have two axes. And again visualise it on a single page, which allows us to understand this space because we can't walk through it like we would our imaginary museum. So let's start to put our different groups into this space. So we saw that our nestlers, there's only a couple of them, so this is a single shell for a whole load of shells. There's usually about 10 shells per species sampling wise of what we could do. And you start to see some striking things. So our byssal attaching, thread attaching scallops have pretty much exactly the same shape as the free living ones. So probably if we think about the evolutionary history of this, the free living ones simply just decided to stop throwing out their threads and just living on the sand. But there's some strikingly weird things going on here. And I want to draw your eyes to those yellow clusters because I'm going to talk about them in just a moment. And those yellow clusters are those gliding scallops. There's two clusters. So that's a bit strange. That sort of started to make our heads scratch. And then we see that our purple ones, which are the recessing ones, sit far off in space. And they're becoming more and more weird looking as they go down to the bottom corner. To the point where they're not just flat shells, they're actually convex. So we started to see these shells. And now we have to think about why the shells exist like this. But a great thing that the method that we used is that rather than linear measurements that simply can get lost, we don't know once you've got a collection of linear measurements – think back to those lines and we just jumbled them up and it's going to be like pick up sticks – but when we use this landmark technique we can immediately recreate the shape. We can see it with our own eyes, the geometry is kept. And so I'm going to explain to you what the major features are, like our caricature, if we were going to caricature the scallop, what our major features of shells are. So over to the left we have basically domed shells that have very large hinges. And then over to the right we have our very flat, even completely convex - as you can see the one on the far right is sort of flipping in on itself – we have completely convex shells. So already you're imagining you're looking through this morpho space, you're looking through this museum and you're seeing these shells. And now you're seeing them animated before your eyes. We go in the other direction, because we want to know what's going on with those yellow dots, so down there we can see again it's flat but it has very large oracles. That's probably being driven by these purple ones that are sitting down there. Which are flat and have very large hinges. But up in the top we have very rounded tiny little hinged animals. And those are the major features of the scallops. So what are those yellow ones? Well this is the most striking thing about it. Turns out that there's two different types. You see two morphotypes. They differ very slightly in the size of the hinge and just how flat they are. And a bit of sleuthing, and a bit of information that we found through the literature, it turns out that people once thought that when they were looking at gliding scallops they should actually look at how fast they can swim. And it entirely correlates with the morphotype A are the fast swimmers, they go for far longer distances than morphotype B. So there was a direct correlation between the shape of the shell and how aerodynamic it is, and how well it moves through the water. To the point where the ones that have that really defined adaptation, and very smooth shell and a tiny little hinge, are the fastest swimmers. Who would have thought the exciting life of scallops. So I've taken you this evening on a journey through the museum of possible forms. In fact just a couple of museums. We couldn't go to all of them, there's so much diversity out there, and there are so many exciting stories that I could have told you, but there simply isn't time. I hope that I have convinced you that this is an intriguing and interesting area of research. That it's worth studying. That it tells us a little bit more about the world that we live in. And in any case you've got to learn a little bit more about something that you probably found tasty. And you'll be able to tell people at the water cooler tomorrow. I wish I'd been able to tell you about these beautiful creatures. The frogs and tadpoles of Australia. Their morpho space is just so complicated and I just couldn't get it in in the time. But it turns out that frogs and their tadpoles are living completely different lives. And that if you see a tadpole in the wild and you look at its body shape it will not predict at all the frog that it's going to turn into. And this is so striking. But this isn't just Australian frogs. Turns out that the same month that we published this paper on Australian frogs another group published on Madagascan frogs and showed exactly the same thing. So this is a ubiquitous pattern in frogs. And what makes it more exciting is that we've got two different life stages of an animal living complete different lives. Adapted to different worlds, and evolving on completely different trajectories. Now if any of you were thinking, yeah, well, great and all, but honestly our money goes into this kind of biology, and this is all that can be done. Well, no, actually these techniques stretch far, far back and much more broadly than just simply distinguishing cuckoo eggs. In fact back in the 1930s the grandfather of statistics, Pearson, who unfortunately didn't create morphometrics but was so close to this fascinating study. It is a 300 page monograph that you can download off the internet. And it's of this gruesome mummy face. And he used exactly the same techniques that I have shown you today to prove beyond an absolute shadow of a doubt, his words, that this skull right here, this mummified face is Oliver Cromwell. And it's Oliver Cromwell, the man who was so treacherous that he was hung and beheaded, and his head was stuck on a spike – and you can see the spike sticking out the top there – they were able to use death masks, and drawings of him. And match those up to measurements of his face. Even pointing out the warts and the moles that he had. And use these same techniques to identify it being Oliver Cromwell's skull. And these same methods are being used in a variety of other things and probably on a daily basis. If you have a phone that looks at your face and recognises your face. Or if you have a phone that recognises your fingerprint it is landmark shape analysis technology that is in fact doing that. So it really is in every part of your life. And finally, for those of you that are particularly interested in reading, but also because I really need to acknowledge that these are the books that have driven and inspired me to think about the geometry of life. To study the way that animals look. They're all pitched at completely different worlds, but they were the ones that made me think that actually in a world of genetics I can continue being a naturalist, and I can continue being an anatomist, and I can make sure that the next generation thinks that it is just as important as I do. Thank you very much.

Q1: **Thank you for listening to the South Australian Museum podcast. Posted by me, Meg Lloyd, and recorded on Kaurna country. This lecture was a part of the Sprig Lecture Series, which commemorates the life of Dr Reg Sprig AO. A most remarkable South Australian who discovered the world's oldest fossilised animals in the Flinders Ranges in 1946. The original theme music for this episode by Peter Saunders. This podcast has been made possible by the support of National Science Week. To see their website www.scienceweek.net.au for amazing science events happening all over Australia. Thank you to Doctor Emma Sherratt for her time both in 2018 and again now. For more information about our museum please visit our website www.samuseum.sa.gov.au, or get in touch by emailing**

programs@samuseum.sa.gov.au. Ngaityalya Nakutha. Thank you and see you later.

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