PROGRAM: 11

Connecting with Networks

Producer: Stewart Boyles
Host: Dan Rockmore

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TIME CODE	AUDIO
00:15	OPENING CREDITS
00:40	HOST The 16th century metaphysical poet John Donne said "no man is an island, entire of itself." In fact, as social beings, we are connected.
00:51	HOST But beyond that, virtually everything we experience – in nature as well as human activity --involves a series of connections that link one thing to another.
01:03	HOST Networks, you might say, make the world go 'round.
01:12	**HOST (V.O.)** **Meet Raymond Price: media tycoon, power broker, and … center of attention. This is his party... his network.**
01:25	**HOST (V.O.)** **Enter Joe Smith. He's just crashed the social event of the year, and apparently doesn't know a soul …**
01:32	**HOST (V.O.)** **But this is one network Joe would like to join. Now, if he could only get connected...**
01:38	JOE Nice party. MAGGIE Mr. Price knows how to entertain...
01:43	JOE You know Raymond Price…? MAGGIE No. I'm to low on that totem pole. Apparently, even my date thinks so...
01:51	JOE Does he know...? MAGGIE I don't know. But I'm sure he knows somebody who knows somebody who… well you know what I mean?
01:57	JOE And he left you just ... hanging here... MAGGIE Disconnected.

02:01	HOST Joe's working the social network for an introduction. But this is just one of countless networks that pervade our lives. Mathematicians define a network very simply - as a collection of entities that somehow relate to each other. Many networks are manmade...
02:17	HOST Communication networks -- Like the Internet, telephone, television, and radio. Transportation networks -- from the airlines to...
02:23	HOST ... country roads, highways, freeways, and railways... Utility networks -- elaborate power grids that stretch across entire continents.
02:33	HOST But most networks are not made by man:
02:35	HOST ... because they're literally a fact of nature: river systems, and the bundles of neurological connections in our brains...
02:42	HOST These networks are all physical - describing a relation created by some physical connection, even if it's something like a cell phone signal. But other networks are more abstract, almost virtual - social networks: networks based on relationships of friendship; food webs: networks based on feeding relationships between species; markets and economies linked together by the flow of capital. In some sense, we could argue that everything on the planet – both living and inanimate is part of one huge, beautiful, but complicated network.
03:16	HOST What do all these networks have in common? Abstractly, they are comprised of intersections or points that we call nodes or vertices that are connected by lines or paths we call edges.
03:23	HOST Now, on this map, for example, cities are nodes and highways are edges.
03:34	HOST Any real-life network can look very messy. In order to get to the heart of the network, mathematicians strip away all the particulars, leaving only the essence, the underlying mathematical graph.
03:50	HOST It was just such a process of reducing a map to its basic components that laid the foundation for graph theory, network theory and topology -- three of the most bountiful areas of mathematics. And it all began with seven bridges --
04:03	HOST -- when one of the greatest mathematicians of all time, Leonard Euler, turns his attention to the famous puzzle of the Konigsberg Bridges in Prussia in 1732:

04:13	**HOST (V.O.)** **Now Konigsberg is split by the river Pragel and smack in the middle of the river is the island Nepuff connected by seven bridges to the mainland. And it was a natural problem both for efficiency and just puzzling to decide was it possible to traverse all seven of the bridges of Konigsberg in one trip without crossing any bridge more then once?**
04:34	HOST Now the puzzle had intrigued the residents of Konigsberg for many years, and it was a popular pastime to try and find the path. Or show that there couldn't be one. And Euler, who lived in Konigsberg, approached the problem in a very novel way: He realized that the problem was not about geography. It had nothing to do with the lengths of the bridges or their distances from one another -- but *everything* to do with their connectivity properties: which bridges are connected to which islands or riverbanks.
05:01	**HOST (V.O.)** **And so for Euler, the land masses where nodes, the bridges were edges and all he had to focus on was how many edges where connected to each node. He described the number of connections as degree.**
05:13	**HOST (V.O.)** **For example, since this node has three edges connected to it, it's said to have an odd degree.**
05:19	**HOST (V.O.)** **Euler noticed that every node, or vertex of the Bridges of Konigsberg had an odd degree: three nodes had degree 3, and one node had degree 5.**
05:29	**HOST (V.O.)** **Euler realized that every time you travel an edge into a vertex, you Have to leave by another edge in order to avoid crossing the previous edge again.**
05:38	**HOST (V.O.)** **That means: if you're never going to double back, the number of edges coming out of each vertex must be twice the number of times you visit that vertex. In other words, every interior vertex of the trip has to have even degree.**
05:50	HOST Now since all the nodes at Konigsberg had an odd number of edges -- each node with an odd degree -- there was no route that crossed all seven bridges without crossing one more than once.
06:01	**HOST (V.O.)** **But what happens if we remove one of the Konigsberg Bridges...**
06:03	**HOST (V.O.)** **This node here has two edges now connected to it, so it has degree 2. This one has degree 4, and 2 of these have degree 3. So now we have two of even degree and two of odd degree**

06:14	HOST Now having done this, in fact, we now can find a path that uses each bridge exactly once. And this is a much more general phenomenon. If you have two vertices of odd degree and all the rest even, then you can always find one of these so called Eulerian paths in the network.
06:30	**HOST (V.O.)** **Now, a second way in which you could also have an Eulerian path is if all the vertices have even degree. In this case, the path will begin and end at the same vertex and its a cycle, or Eulerian cycle.**
06:43	**HOST (V.O.)** **But since all the nodes of the original Konigsberg Bridges are with odd degree, we cannot complete either the Eulerian Cycle or the Eulerian Path.**
06:53	HOST Euler gave us a way to talk about graphs that can be used to express today's networks mathematically. And we can begin to see how his theories are so important to the highly connected world that we live in today -- even with something as basic as a municipality planning its snowplow routes:
07:09	**HOST (V.O.)** **Intersections are the nodes on this graph, and the streets are the edges.**
07:13	**HOST (V.O.)** **As the plow finishes one street and hits the intersection, it starts plowing down another street. And when it does, it leaves the intersection - as long as the intersection has even degree. That would mean that there is another edge coming into the intersection and an edge going away from it.**
07:28	**HOST (V.O.)** **Remember, if all the nodes have even degree, we have an Eulerian cycle. So if the snowplow travels a route in which all the roads are hit only once, its route is more efficient because the snowplow is not retracing streets that have already been cleared.**
07:43	HOST In fact, if we think about networks as being about communication, then the idea of connectivity is crucial to understanding how they work. At the very least, it's critical that any one point be reachable from any other point, because they can only interact if two nodes are linked either directly or indirectly. But connectivity is about more than just being connected. It's also a matter of design and measurement , which are things that airlines have to take into consideration when they're planning their routes.
08:11	**HOST (V.O.)** **For example, it may not be economically wise for Oceanic Air to run direct flights from Birmingham, Alabama to Boise, Idaho, but...**
08:19	**HOST (V.O.)** **...they can certainly get you there through connections, like the hubs in Houston or Denver.**

08:25	**HOST (V.O.)** **And usually, you can come back.**
08:27	**HOST (V.O.)** **An airline network is a directed network, one in which the edges between nodes have an orientation or direction. Most airline networks would actually have two directed edges between nodes, one in each direction. Directed networks add an extra level of complexity to the situation since generally the direction of an edge indicates that you can only travel one way on the edge. Maybe that's what accounts for the confusions of modern air travel.**
08:52	**HOST (V.O.)** **But the most basic kind of network is the undirected network, like that of the Bridges of Konigsberg, where the direction traveled across each edge is irrelevant. For argument's sake, let's assume that our Oceanic Air company is smart enough to have all connections between cities work in both directions. When we represent the airline's network by its underlying undirected graph, we see that it is a connected network -- any node is reachable from any other.**
09:20	**HOST (V.O.)** **Once we know is connected, we can ask how tightly it is connected. We can measure this in terms of the diameter of the network.**
09:29	**HOST** **Say we have an airline that not only serves Birmingham, Houston, Denver and Boise, but also Albuquerque, Kansas City, Memphis and New Orleans. Let's call these cities our nodes.**
09:41	**HOST (V.O.)** **Remember, we can't get directly from Birmingham to Boise, but we can make some connections to get there. So let's call the flight paths our edges.**
09:50	**HOST (V.O.)** **The fewest numbers of edges needed to get between two cities is called the distance. So the distance between Birmingham and Boise is two. We can now measure the diameter of the network, which is the greatest distance between any two nodes. It is the greatest number of flights you must take from one place to another. Since Memphis only connects to Birmingham the diameter of this flight network is three. A diameter of three means no more then two transfers. When edges go away connectivity generally decreases.**
10:20	HOST These statistics get at the large-scale structure of the network, but what about small-scale properties, the sort of "clumpiness" of the network? One way to measure these properties is to show, for any given node, what fraction of nodes in the graph it's connected to. Another way is to ask, what is the probability that it's connected to any other node? A node connected to a large proportion of the graph is a hub, like an airline hub, which is on average connected directly to more cities than non hubs

10:50	HOST This is a simple notion of clustering, but there are more subtle notions inspired by the considerations of social networks - there instead of asking how likely it is that I'm friend's with a random person in the world, we ask how likely it is that two of my friends are themselves friends? In network lingo we're asking how likely is it that two nodes connected directly to me are themselves connected - that our three little nodes complete a triangle? It turns out that in social networks, the likelihood of these triangles is higher than you would expect, and that those people who find themselves at the hub of many triangles are the ones to know in a social network. Let's see if our friend Joe can find one of these highly connected and clustered individuals.
11:40	HARRY Looks like Price is in true form.
11:44	SARAH Who's that? JOE Nice Party
11:47	TEDDY Never seen him before. JULIA (slight gasp) JAMES You know him? JULIA Yeah, from college. We dated.
11:52	HARRY Hey, he's talking to my date.
11:54	**HOST (V.O.)** **You might say Joe is trying to take advantage of what we call small world structure - trying to connect with people he doesn't know through other peoples' relationships.** JOE Hey. I think know her. Julie, Julia. **HOST (VO)** **It looks like Joe just found one of those connections…**
12:12	Dan Rockmore: So Joe is trying to work the social network here, and it turns out that if you know a little bit of mathematics, it's easier to do it. So we're lucky to have with us today Raissa D'Souza, who's a professor at UC Davis and an expert in network theory.

12:22	Risa, Joe's trying to make his way through the social network. Social networks are a little complicated, so is there an easier example that we can start with to explain what it is he's trying to do?
12:34	The simplest network we might think of is highly ordered and regular, so we might even think of like a grid or a piece of graph paper, so a regular lattice where everybody has four links to their nearest neighbors, and they have four links to their nearest neighbors,
12:49	D’Souza: So the geometry is perfectly ordered and regular. And it's much easier to do some mathematics with regular structures like that, so we know the connections, so we would know how to navigate through a network like that.
13:05	D’Souza: And cover all the edges in a really efficient manner.
13:08	Rockmore: So it’s one thing to be presented with an ordered network, like the streets of New York for example, and it’s completely believable that we can understand everything about those. But an amazing and beautiful theory is that we can also understand everything about a totally random network. And, you could have many different models of what does it mean to have a random network, but one of the more interesting ones is one due to two Hungarian mathematicians – Paul Erdos and Alfred Renyi. So maybe you could explain to us what does it mean for a network to be random.
13:36	D’Souza: In contrast to the ordered graph, where everybody has the same number of connections and regular geometry, we might think about those edges being there or not being there with some probability. So we might want to start out in the extreme example where we’ll think of everybody being connected to everybody else in the network.
13:52	D’Souza: And we typically call that the complete graph.
13:56	D’Souza: And how we’re going to make it into a random network is we’ll go through edge by edge and flip a coin to decide whether that edge stays or goes. And I have a coin with me --
14:05	Rockmore: Math in action.
14:07	D’Souza: So in this case, we’re going to let the edges exist with probability fifty/fifty.
14:10	Rockmore: Okay.
14:11	D’Souza: So why don’t you choose an edge.
14:14	Rockmore: All right. I’m going to take the one in the upper corner over there.
14:18	D’Souza: And that’s a tails, so we’re going remove that edge.
14:21	Rockmore: All right. Now I’m going to go for something right in the middle. That one.
14:26	D’Souza: And that one’s a head, so we’re going to keep that.
14:28	Rockmore: One more over in the lower quadrant there.
14:30	D’Souza: And that one’s a tail, so we’re going to remove that edge.
14:32	Rockmore: Yeah, we’re going to chop that one out.
14:35	D’Souza: And now we’ll go through…
14:36	Rockmore: So we would do that for every single edge in the network and then we’d get some structure, which is random in the sense it was constructed by this random process.

14:44	Rockmore: If you had a hundred mathematicians flipping a hundred coins with a hundred complete graphs, you could say on average what the properties of one of those graphs would be.
14:52	D'Souza: Exactly.
14:53	Rockmore: But the way that networks generally come about in the world, of course, is in a more evolutionary way. You start off probably with many disconnected things and then slowly but surely they get connected in some fashion.
15:04	D'Souza: Yeah. And we can think of a whole equivalent kind of process where we're growing a random graph that will get us to the same point as where we started from the complete graph and pruned edges. So, I have an example to tell you about with buttons and thread.
15:20	D'Souza: What we're going to do is think of each button as a node. And they're all disconnected, so no one has any edges yet. And I'm going to take some thread and start choosing two buttons at random that aren't yet together and sew them together. And now I'll find another two buttons that aren't yet connected and connect them. And I'll keep drawing two buttons at random and connecting them. Each time I'm going to find an edge that isn't yet present and add it
15:45	Rockmore: Put it in.
15:46	D'Souza: So I'm just going to draw an edge, uniformly at random, from all the edges that could be there.
15:49	Rockmore: From all potential edges.
15:50	D'Souza: All the potential edges
15:51	Rockmore: that could be there.
15:52	D'Souza: And as we start joining buttons together, initially we will have two buttons and then it might become three buttons or four buttons. And whatever small group of buttons are connected to each other, we call a component. So they're connected to each other but not to other places. So they're small clumps.
16:10	Eventually we'll get to the point where we're starting to merge components. So I've…
16:13	Rockmore: So we begin to get something very large and cohesive.
16:16	D'Souza: And what's fascinating of the Erdos/Renyi random graph is that there's a critical point where I start adding one or two edges and it changes the underlying properties. and suddenly all those smaller components merge together and I get a giant component. So, just one or two edges changes the underlying property dramatically. So you might think about some networks where we really want to have connectivity. Like in a telecommunications network. And then in the opposite point of view, we might think about epidemiology.
16:50	Rockmore: Right. Where you want things…
16:51	D'Souza: Flow of diseases.
16:52	Rockmore: …to be very disconnected…
16:53	D'Souza: We don't want giant components.
16:54	Rockmore: …so that actually the disease can't get across from one community to another. Right.

16:57	D'Souza: Exactly. So that phase transition is really changes the underlying properties of the graph. And that was one of the most amazing things of the Erdos/Renyi random graph model. It's so simple. It tells us the ensemble of random graphs, but it has this beautiful property of a phase transition.
17:14	Rockmore: So on the one hand, we understand the totally regular. And we have a lot of understanding of what happens randomly. But the social network, like the one that Joe's trying to navigate there to get to the tycoon, is somewhere in-between.
17:27	D'Souza: That's right. Like most networks in reality. And there are mechanisms that we think are important for how people interact with each other.
17:36	Rockmore: And we can turn that into network language, right? That if I'm here and I have a friend here, we're connected by friendship. And I have another friend; I'm also connected to this friend by friendship. Then the presumption is, actually, that there's a triangle of friendships. And my friends know each other.
17:50	D'Souza: Exactly, we're trying to understand potential mechanisms that we think drive human behavior. And then looking at example networks to see whether our theories are backed up by data from the real networks.
18:03	Rockmore: All right. Well, let's see if Joe has a good understanding of what a social network looks like.
18:08	D'Souza: Great
18:10	JOE Julia! Julia Wells! I haven't seen you since… JULIA Joe. What brings you here? JOE Well, honestly, I'm crashing the party to meet Mr. Price.
18:19	JOE Joe Smith. Obviously, you know Maggie... Everyone, this is Maggie. MAGGIE Hello, nice to meet you JOE Maggie says you might know somebody...
18:27	HARRY Well, I know several people. Sounds like you are here to do some networking. JOE Absolutely. Let me show you something.
18:32	**HOST (V.O.)** **Looks like Joe is on his way — taking advantage of networking opportunities to connect to Price.**

18:38	HOST It appears that the connected component he's joined is not yet part of the giant component that surrounds Price. But knowing Joe, they won't stay disconnected for long...
18:48	JOE ...I think I might be able to reach rapid phase transition fairly quickly... TEDDY Clever. How'd you figure that out?
18:56	JOE I'm a graduate student: mathematics, network theory. So Harry, who do you know? HARRY Well, I know a broker, whose partner is doing some high level consulting for price ventures, Wanda Watson, I believe she's right over there...
19:12	JOE Let's make this happen
19:17	Rockmore: So what Joe is taking advantage of is this extra structure that is in a social network. In fact, he's really taking advantage of something that we call the Small World Structure of the social network.
19:28	D'Souza: And what characterizes something as a small world is that the distance between any two individuals is relatively small. And there's also many more triangles than we would expect in the random graph.
19:38	Rockmore: Because of that friends of friends kind of thing.
19:42	D'Souza: Exactly.
19:43	Rockmore: So, Joe's really taking advantage of some mathematical ideas here, is that right?
19:46	D'Souza: He is. He's learning how to navigate through that small world.
19:50	Rockmore: Alright. Terrific. Well, thanks so much for helping us figure this out.
19:53	D'Souza: Oh, my pleasure.
19:56	Rockmore: So social networks are just one kind of evolved network. And another kind are food webs, networks that exist between animals. And we're going to visit now with Neo Martinez, a scientist at the Pacific Eco-informatics and Computational Ecology Lab in Colorado.
20:11	NEO MARTINEZ: I'm Neo Martinez; I'm the director of the Pacific Eco-Informatics and Computational Ecology Lab.
20:20	MARTINEZ: Math is very important to our studies.
20:23	MARTINEZ: We represent ecosystems as networks by designating which species live in a habitat and who eats whom among those species. So the network has species as the nodes and feeding relationships as the links between the nodes.
20:40	MARTINEZ: Network theory is an increasingly used body of theory to understand systems. Many scientists are realizing it's a wonderful framework to basically connect the dots within their systems.

20:54	MARTINEZ: The advantage we gain by viewing ecosystems as a network is the ability to track effects from one species to other species within the network.
21:06	MARTINEZ; One of the main other bodies of theory that we use is the theory of non-linear dynamics."
21:13	MARTINEZ: -also known as chaos theory and we use that theory to structure equations that calculate the energy flow through our ecosystem from plants say to herbivores to carnivores.
21:27	MARTINEZ: it's important to understand the effects of species on one another because that is changing quite a bit these days. Many species are going extinct due to human activity. And also new species are invading ecosystems due to human activity.
21:44	MARTINEZ: Ecosystems form much more tightly connected networks than many other networks. What happens is that each species is typically within three links of all other species within the ecosystem. That's a lot closer than say the six degrees of separation that's supposed to separate human's familiarity networks- who knows who within say the US. So these are tight networks where effects on one species can propagate to many other species quite quickly.
22:23	MARTINEZ: One of the most famous examples of the effects of one species on the others within the eco-system, through the network that we have been studying, is the sea otter example. Back in the 1800s, the Russians and several other western countries paid native Americans to hunt sea otters pretty much to the extinction of them and many habitats across the pacific coast. When the otters went extinct the sea urchins, what the otters ate, started getting really , really abundant. Those urchins ended up eating a lot more kelp then usual. And they pretty much destroyed the kelp forest. So the whole ecosystem that depended on the kelp was wiped out.
23:12	MARTINEZ: So one of the neat, sort of networky things about this system is that if you look at this plant, this lupine, you'll find some ants walking all over it, they sort of patrol it. But what happens many plants in this habitat have nectaries—little places that provide food for the ants. And in return, the ants walk all over the plant and wipe out the aphids—little plant-sucking insects that would normally eat a lot more of the plant than the plant gives to the ants. And so by giving the ants a little bit of food, they save themselves quite a bit of damage by the aphids.
23:54	MARTINEZ: Our studies of ecological networks are important to people because people want to know if they can depend on their food to be there, and if they can depend on their predators not being there.
24:06	MARTINEZ: I think one of the most fun parts of this research for me is the fact that it really gives us the opportunity to figure out how the whole system operates. A lot of science is what is called reductionist science—looking at all the little parts. Network studies allow us to put those parts together and understand how the whole system operates.
24:29	MARTINEZ: The combination between the intellectual intrigue of putting all these pieces together and being able to visit beautiful places like this makes my job rock.

24:45	HOST Animals eating each other is one thing, people making friends is another. And remember that social networks are generally small world networks –ones with lots of triangles and small diameters.
24:56	HOST ... which brings us back to Joe and the party, where some classic small world dynamics are taking place. Most people here have only a few connections, but a few people have high connectivity. Because of this, It seems any given person is only a few handshakes away from anyone else by way of introduction.
25:21	Joe: Hi, I'm Joe Smith Wanda: Hi, Wanda Watson. Nice to meet you. Joe: Nice to meet you Wanda. I believe you know Harry. Wanda: Oh yes, Harry. It's good to see you again. Harry: Good to see you again. Joe: Harry and I met through Maggie
25:31	PRICE I hear that Wanda would like wants to introduce someone to me... Is that him? FLUNKY Who?
25:35	PRICE The guy with Wanda Watson... FLUNKY I'll go get them...
25:38	**HOST (V.O.)** **What we're seeing here now is the emergence of a giant component, that is, a connected subset of the graph that includes a very large fraction of the vertices. This rapid phase transition would have occurred even if our guests had been making friends randomly. But with Joe's focus on making friendships to reach Raymond Price, we see it come about even more quickly...**

26:00	PRICE Wanda — you're looking lovely. WANDA Thank you Raymond.
26:03	 WANDA Allow me to introduce a very impressive young man I've just met... Raymond Price, Joe Smith. PRICE Welcome to my party, Joe. It seems we know a lot of the same people... JOE Thank you, sir. I can't tell you what an honor it is to make this connection...
26:17	PRICE Seems like I've known him almost an hour now.
26:24	HOST Networks. We're all surrounded by and part of a vast array of them. They bind us together, connecting information, people, animals... even snowplows. Mathematics helps us understand how those networks grow, how they operate, how they affect us.
26:40	HOST Indeed, no man... no person... no animal ... no object, organic or inorganic ... is an island.
26:50	CLOSING CREDITS