Have you ever wondered how you would be able to navigate yourself through the labyrinthine street network of a town without any central knowledge base like a map or a GPS device? One thing is sure, to wander around would result in an inadmissibly long journey, even in a smaller settlement. How about the letter in the social acquaintance network of Milgram’s small world experiments? Is it a feasible scenario that the letter just accidentally finds its way towards an addressee without any central guidance for the messengers passing it randomly to each other? With only a maximum of ten bridges across Königsberg’s four islands resulted in 2330 different paths; what would happen in a network containing 300 million nodes with a hundred times more edges between them? The turmoil would be inconceivable!

The very existence of short paths between the nodes of a network is one thing, to find them is completely another thing. It is reasonable to assume that there must be some landmarks or traffic signs in even the smaller networks if we are to find an adequately short way through it. There must be some internal logic that helps us to navigate from node to node towards our predefined destination without spending too much time roaming in the maze.

The internal logic of a network is something that is, on one hand, strongly connected to its outlook or construction. However there is sometimes something that is even more important than that: it is the rules of how to use paths among the nodes. In real networks, it is not uncommon that, although a path exists between nodes, it cannot be used due to some rules. For example think about a traffic sign that indicates one cannot enter a road unless invited by a resident. Just like the sign at the house of Winnie the Pooh’s friend Piglet: “TRESPASSERS W.” (Or was it really the name of his grandfather?) Or what about a carpool lane where a path can

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Orr was crazy and could be grounded. All he had to do was ask; and as soon as he did, he would no longer be crazy and would have to fly more missions. Orr would be crazy to fly more missions and sane if he didn’t, but if he was sane, he would have to fly them. If he flew them, he was crazy and didn’t have to; but if he didn’t want to, he was sane and had to.

—Joseph Heller, Catch-22, Simon & Schuster 1961
only be used by cars shared by multiple travelers? Those also very much belong to the internal logic of a network: it is about how a network may be used. In the following let us take a look at some more complex examples, one from history and one from technology: the military organization network, and the Internet.

Military organizations have a strong internal logic: a hierarchy. As we will see, this strict hierarchy has a fundamental influence on the internal communication paths. The network representation of an imaginary military organization is shown in Fig. 5.1. On the lowest level of the hierarchy, there are the privates (Pvt Gump, Ryan and X). They are usually under the command of a sergeant (Sgt Drill and Horvath). Above sergeants, we find lieutenants (Lt Dan and Dewindt), commanded by the captain (Captain Miller). The typical order of command in the military is that soldiers at lower levels of the hierarchy report to one level above, while higher level soldiers give commands to one level below. For example, the path of some imaginary information from Pvt Gump to Pvt Ryan could be: (1) Pvt Gump reports to Sgt Drill, (2) Sgt Drill includes this information in his report to Lt Dan, (3) Lt Dan also includes the info in his report to Captain Miller, (4) the captain makes a decision and gives a command to Lt Dewindt, (5) Lt Dewindt commands Sgt Horvath accordingly, (6) Sgt Horvath then gives the corresponding command to Pvt Ryan. Such a path may describe a situation where Pvt Gump observes something important in the battlefield which should be reported to higher levels, from which the reacting commands seep down to the lower levels.

How does this regular path relate to shortest paths? In our imaginary organization, this regular path is also the shortest path, as we cannot find a path between Pvt Gump and Pvt Ryan with fewer steps. In fact, the organization is so simple that we only have one reasonable path between Pvt Gump and Pvt Ryan. All other paths will contain loops, meaning that there is at least one soldier that appears twice on the path. Let’s make our organization a little more complex and realistic.

Consider that Pvt X is doing a special service for the military and spends half of his day under the command of Sgt Drill and the other half under Sgt Horvath (i.e., he is part of a liaison squad enabling communication between the units commanded

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**Fig. 5.1** Military hierarchy
The network representation (see Fig. 5.2) of this modified organization differs in only one edge going between Pvt X and Sgt Horvath. This small modification, however, uncovers an interesting phenomenon. In the modified network, the shortest path between Pvt Gump and Pvt Ryan is no longer through lieutenants and captains. The regular path is unchanged, but the shortest path is Pvt Gump → Sgt Drill → Pvt X → Sgt Horvath → Pvt Ryan. The corresponding story could be that Pvt Gump reports to Sgt Drill, who orders Pvt X to report something to Sgt Horvath, who gives the command to Pvt Ryan. This absolutely can be done and fits within the norms of the army, but it is rather unusual. The shortest path seems odd and breaches the everyday logic of the military network. We can say that the shortest path is theoretically usable, but it seems practically non-traversable. Moreover, in this case, the regular path coinciding with the internal logic of the network is longer than the shortest possible path.

Besides the clear conflict between the shortest path and the regular path, implementing the two paths will have different effects on the organization. By using the regular path, high-level decision makers are notified about the event happening at lower levels and can make use of this knowledge in later decisions. The usage of the shortest path, while it enables a faster reaction, prevents the information from escalating and leaves the army in a different state. Can such illogical but short paths be used within the army under any circumstances? Are there unusual situations in which the everyday practices can be overridden? Well, it depends on the level of unusuality. Let’s illustrate this with a short story about Hungary’s participation in the Second World War.

The participation of the Hungarian 2nd Army in the Second World War on the side of Nazi Germany was undoubtedly surrounded by a great amount of unusuality. There are many books[24] covering the stories of the battles facing Russian soldiers on the eastern theatre of the war near the Don River. During its 12 months of activity in 1942–1943 on the Russian front in the framework of the Operation Barbarossa, the 2nd Hungarian Army’s losses were enormous. Of an initial force of about 200,000 Hungarian soldiers 125,000 were killed in action, wounded or captured. These losses were the result of the power of the Russian army, the extreme cold
and the commanding structure of the German Army Group B under which the Hungarian 2nd Army appeared as a sub-unit. The commander of the Hungarian 2nd Army was Gusztáv Jány (see Fig. 5.3). A German liaison staff commanded by General Hermann von Witzleben was assigned to work under the Hungarian army, coordinating the movements of the German and Hungarian armies. Thus his troops were somewhat subordinates of the two armies at the same time. The German Army Group B was commanded by Maximilian von Weichs, who received orders from the Wehrmacht high command and eventually from Adolph Hitler.

After a few months of Hungarians and Russians peering at each other on the banks of the Don, the Russians began their counter-attack on the front line of the Hungarian 2nd Army on 12 January 1943. During this attack, most of the Hungarian units were quickly encircled and either annihilated or forced to open terrain where they succumbed to the extreme cold. Facing the situation and the casualties Jány tried to obtain a command to withdraw his troops, using the standard chain of commands in the army. He sent messages to his superiors with the immediate request for retreat. After days of bloody massacre, the answer from the German high command remained the same: “In accordance with the Führer’s decision, the positions . . . must be held to the last man under all conditions”. As a parallel action, on 15 January, Weichs asked Witzleben to meet Jány and to unofficially persuade him to order the immediate retreat. The reason for this unofficial action was that Weichs himself did not want to give a withdrawal order contradicting Hitler’s instructions. On 17 January Jány eventually ordered his troops to commence
retreating. It was only on 22 January when the headquarters of Army Group B decided, with Hitler’s permission, to withdraw the Hungarian 2nd Army from the front line.

So what happened? Jány tried to use the regular path (chain of command) to report and react according to the decision of high-level decision makers. However, his situation was really unusual. He lost thousands of soldiers day-by-day and the regular path was too slow to properly react to the situation. While Weichs and other German commanders on site agreed with Jány about the immediate retreat, they didn’t want to conflict with higher decisions. Instead, Weichs unofficially notified Jány through his German subordinate, by communicating that “high orders should always be interpreted in accordance with the situation”. This act convinced Jány, that he really had his last men standing, so it was time to withdraw his troops. As a result, he retreated 5 days before the official permission. Those few days saved thousands of his people. In this case, the non-regular path was undoubtedly odd but worked and saved lives. How frequently do such events, that require non-regular paths, happen in the military? Well, horse sense suggests that if such events were prevalent, then the military would not work at all. So we should expect the great majority of paths to be regular and just a small portion of the paths to be non-regular.

The large scale Internet also possesses definite internal logic. It does in spite of the fact that it has a strong self-organizing characteristic in its evolution. Indeed, the Internet has grown into an intricate interconnection system through the uncoordinated process of nodes freely joining to the network. Although this joining process was truly without central coordination, it wasn’t without laws. Relations between nodes have evolved to show a similar structure to what we saw in the military example. To shed some light on how this can happen, let’s follow the imaginary story of the people of the little town Castle Rock, Maine.

During strong winters in Castle Rock, people are doomed to stay in their houses. One day lonely locals decide to connect to each other to communicate (e-mail, chat, video chat, etc.) by using their computers. Out of that purpose, they form a civil company that creates a local network across the whole village. Interestingly, almost in parallel, a similar series of actions takes place at the nearby settlement of Salem’s Lot. No wonder that soon the two towns decide to establish a communication cable to connect to each other.

People seem to be happy for a while, but not much later it comes to the locals’ knowledge that an English town, Dunwich, also built a local area network for similar purposes. Would it be possible to also connect Castle Rock to Dunwich? The distance seems to be too much for the poor little town. Fortunately an entrepreneur at the Main County Trans-Atlantic Co. (MCT) undertakes the task of building an underwater cable through the Atlantic Ocean and connects the MCT to Castle Rock and than to Dunwich. Thus providing long distance communication services to both towns for a monthly fee. Our newly born communication network, at this state, has four nodes: Maine County Trans-Atlantic Co, Dunwich, Castle Rock and Salem’s Lot. The little town of Castle Rock initiated the building of a large-scale computer
network, the nodes of which are networking companies. It is just like a tiny Internet (see Fig. 5.4).

Soon enough, however, conflicts arise when people at Salem’s Lot take to regularly using the network spending most of their spare time communicating with the nice people from Dunwich! Notice that Salem did not spend money itself on building the network or buying the service from MCT, even so they can reach Dunwich using the networking resources of the nearby Castle Rock. But is it fair to Castle Rock to load its network, possibly slowing its communication service, due to the traffic of Salem’s Lot? Through a connection that was initially established out of mutual agreement to exchange network traffic free of charge? Castle Rock pays Maine Trans-Atlantic to reach Dunwich, but it is free for Salem’s Lot! The path from Salem to Dunwich does not seem to be regular at all! It is not in the logic of the network to use such a path. Castle Rock would surely cease the cooperation or ask for some compensation, thus making Salem’s Lot a customer of Castle Rock.

Furthermore, a more interesting situation arises when the people of Castle Rock begin to feel unsafe about the single existing communication path to Dunwich. A Canadian company called Canadian Federal Communications (CF), noticing the business opportunity, comes forward also offering data transit services across the Atlantic for a fee. So, Castle Rock also chooses to connect to Canadian Federal as a backup plan for when the Maine Trans-Atlantic link goes down due to some error. Our tiny Internet has grown into a complex 5-node super-highway (see Fig. 5.5).
Fig. 5.5 A tiny model of the Internet initiated by the people at Castle Rock to communicate with the outside world by connecting nearby town Salem’s Lot and Dunwich in England by using the transit services of Main County Trans-Atlantic (MCT) and Canadian Federal Co. (CF) as a backup route

All seems to be fine at the moment and will remain so as long as the Canadians do not decide to communicate with Maine County Trans-Atlantic, generating an even more serious conflict. Currently MCT and CF are only connected via their common customer’s network. Should Castle Rock allow the CF to communicate with MCT? Absolutely not! It is not logical to provide transit services to them for free! The resources alone would not be enough to serve the transmission requirements of such large companies. Canadian Federal and Maine Trans-Atlantic should build their own network or use the transit services of even larger telecom service providers. It does not matter if the path connecting the two becomes longer as using the shortest path through a customer is not a viable solution! It is not considered to be regular!

As we can see the labyrinthine network, which we now call the Internet, connecting the telecom companies of the world also has some structure to it and works along some rules. Similarly to the military system, it contains a communication hierarchy formed by customer-provider relationships generating strict communication policies governed by complex business interests.

Is it possible that other networks also have similar internal logic? Is it possible that similar reasons can make paths longer than the shortest path? It is time to not just philosophies about real paths, but to do some ground truth measurements and see what phenomena are actually supported by real data.
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