# Chapter 2
# Protocol Stack of WSNs

*Etiquette is protocol, rules of behavior ..*
*How a gentleman opens the door for a lady, how he smiles and handshakes.*

## 2.1 Introduction

A *protocol*, etiquette, code of conduct, is a set of rules that govern a certain behavior, in social or diplomatic activities, at work, when driving, etc. Socially, there is a dress for night parties, there is a way to put off a coat, to sit, eat, and speak. Diplomatic activities are framed in strict protocol rules that determine who comes first, who is next, who will be to the right, who speaks; deviating from such rules is a serious breach of job duties. A protocol is also the draft of a treaty or agreement. At work, there are limitations to what can be said in public, to what can be worn, to where to eat or smoke. When driving, there are rules to follow a lane or to change lanes, to surpass, to honk, to speed limits. Protocol rules may be imposed by administrative regulations, or by social habits, either way they are followed, and monitored, a person is appreciated with regard to how far he clings to protocol guidelines. In communication networks, protocols govern, determine the functioning specifications and guidelines, and guarantee how networks fulfill their intended use.

A wireless sensor network is an ad hoc arrangement of multifunctional sensor nodes in a sensor field, disseminated to gather information regarding some phenomenon. Sensor nodes can be densely distributed over a large and may be remote area and collaborate their efforts to the benefit of the network to the extent that even if a number of nodes malfunction, the network will continue to function. There are two main layouts for wireless sensor networks. The first is a star layout where the nodes communicate, in a single hop, directly to the sink whenever possible and peer-to-peer communication is minimal. In the second, information is routed back to the sink via data passing between nodes. This multi-hop communication is expected to consume less power than single-hop communication because nodes in the sensor field are densely distributed and are relatively close to each other.



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As previously stated, wireless sensor networks differ from traditional ad hoc networks in a few very significant ways:

- Power awareness. Because nodes are placed in remote, hard to reach places, it is not feasible to replace dead batteries. All protocols must be designed to minimize energy consumption and preserve the life of the network.
- Sensor nodes lack global identifications (IDs), so that the networks lack the usual infrastructure. Attribute-based naming and clustering are used instead. Querying WSNs is done by asking for information regarding a specific attribute of the phenomenon, or asking for statistics about a specific area of the sensor field. This requires protocols that can handle requests for a specific type of information, as well as data-centric routing and data aggregation.
- Position of the nodes may not be engineered or pre-determined, and therefore, must provide data routes that are self-organizing.

A protocol stack for WSNs must support their typical features and singularities. According to (Akyildiz et al. 2002), the sensor network protocol stack is much like the traditional protocol stack, with the following layers: application, transport, network, data link, and physical. The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation and data encryption. The data link layer is responsible for the multiplexing of data streams, data frame detection, medium access and error control. It ensures reliable point-to-point and point-to-multipoint connections in a communication network. The network layer takes care of routing the data supplied by the transport layer. The network layer design in WSNs must consider the power efficiency, data-centric communication, data aggregation, etc. The transport layer helps to maintain the data flow and may be important if WSNs are planned to be accessed through the Internet or other external networks. Depending on the sensing tasks, different types of application software can be set up and used on the application layer.

WSNs must also be aware of several management planes in order to function efficiently, specifically, mobility, service (QoS) and security management planes. Among them, the functions of task, mobility and power management planes have been elaborated in (Akyildiz et al. 2002; Wang and Balasingham 2010). The protocol stack and the associated planes used by the sink, cluster head and sensor nodes are shown in Fig. 2.1. The power management plane is responsible for minimizing power consumption and may turn off functionality in order to preserve energy. The mobility management plane detects and registers movement of nodes so that a data route to the sink is always maintained. The task management plane balances and schedules the sensing tasks assigned to the sensing field and thus only the necessary nodes are assigned with sensing tasks and the remainder are able to focus on routing and data aggregation. QoS management in WSNs (Howitt et al. 2006) can be very important if there is a real-time requirement with regard to the data services. QoS management also deals with fault tolerance, error control and performance optimization in terms of certain QoS metrics. Security management is the process of managing, monitoring, and controlling the security related behavior of a network. The primary function of security management is in controlling access

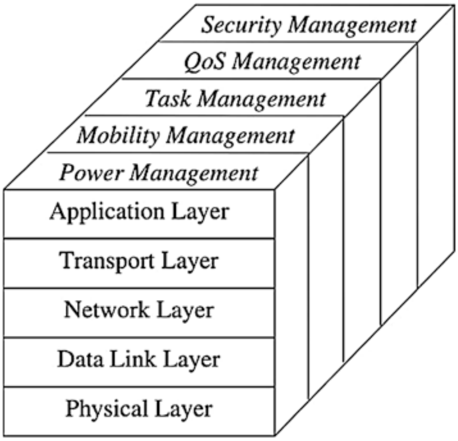


**Fig. 2.1** Protocol stack of WSNs (Wang and Balasingham 2010)

points to critical or sensitive data. Security management also includes the seamless integration of different security function modules, including encryption, authentication and intrusion detection.

## 2.2 Physical Layer

In many wireless sensor networks, the number and location of nodes make recharging or replacing the batteries infeasible. For this reason, energy consumption is a universal design issue for wireless sensor networks. Much work has been done to minimize energy dissipation at all levels of system design, from the hardware to the protocols to the algorithms. Hence to the network, it is important to appropriately set parameters of the protocols in the network stack. At the physical layer, the parameters open to the network designer include, modulation scheme, transmit power and hop distance. The optimal values of these parameters will depend on the channel model. When a wireless transmission is received, it can be decoded with a certain probability of error, based on the ratio of the signal power to the noise power of the channel (i.e., the SNR). As the energy used in transmission increases, the probability of error goes down, and thus the number of retransmissions goes down. Thus there exists an optimal tradeoff between the expected number of retransmissions and the transmit power to minimize the total energy dissipated to receive the data (Holland et al. 2011).

At the physical layer, there are two main components that contribute to energy loss in a wireless transmission, the loss due to the channel and the fixed energy cost to run the transmission and reception circuitry (Heinzelman et al. 2002). The loss in the channel increases as a power of the hop distance, while the fixed circuitry energy cost increases linearly with the number of hops. This implies that there is an optimal hop distance where the minimum amount of energy is expended to send a

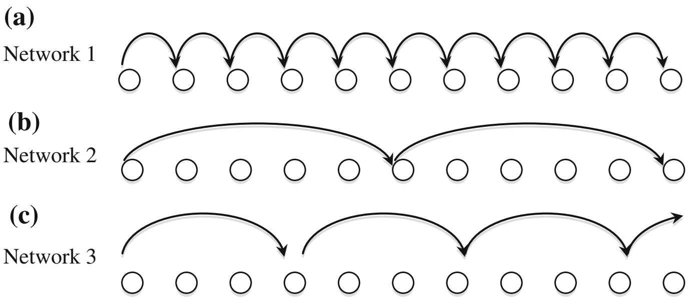


**Fig. 2.2** Instances of a linear wireless network (Holland et al. 2011). **a** Network 1 has a short hop distance. **b** Network 2 has a long hop distance. **c** Network 3 has the optimal hop distance

packet across a multi-hop network. Similarly, there is a tradeoff between the transmit power and the probability of error. In this tradeoff, there are two parameters that a network designer can change to optimize the energy consumed, transmit power and hop distance. The third option for physical layer parameter selection is much broader than the other two. The coding/modulation of the system determines the probability of transmission success, changes in the probability of a successful transmission lead to changes in the optimal values for the other physical layer parameters (Wang et al. 2001).

To illustrate these physical layer tradeoffs, consider the linear network shown in Fig. 2.2 (Holland et al. 2011). In this network, a node must send data back to the basestation. The first physical layer consideration is hop distance. In the first case (Network 1), the hop distance is very small, which translates to low per-hop energy dissipation. Because the transmit energy must be proportional to $d^n$ where $n \geq 2$ and $d$ is the distance between the transmitter and receiver, the total transmit energy to get the data to the basestation will be much less using the multi-hop approach than a direct transmission (Heinzelman et al. 2002). However, in this network, the main factor in the energy dissipation of the transmission is the large number of hops. The fixed energy cost to route through each intermediate hop will cause the total energy dissipation to be high.

In the second case (Network 2), the hop distance is very large. With so few hops there is little drain of energy on the network due to the fixed energy cost. However, there is a large energy drain on the nodes due to the high energy cost to transmit data over the long individual hop distances. With a large path loss factor, the total energy in this case will far exceed the total energy in the case of short hops. Thus it is clear that a balance must be struck, as shown in Network 3, so that the total energy consumed in the network is at a minimum.

Several standards that enhance low power communication, as required for WSNs, are laid out in Chap. 1.

## 2.3 Data Link Layer

The responsibilities of the data link layer are the multiplexing of data streams, data frame detection, medium access (MAC) and error control. A wireless sensor network must have a specialized MAC protocol to address the issues of power conservation and data-centric routing. The MAC protocol must meet two goals. The first is to create a network infrastructure, which includes establishing communication links between may be thousands of nodes, and providing the network self-organizing capabilities. The second goal is to fairly and efficiently share communication resources between all the nodes. Existing MAC protocols fail to meet these two goals because power conservation is only a secondary concern in their development. Also, wireless sensor networks have no central controlling agent and a much larger number of nodes than traditional ad hoc networks. Any MAC protocol for wireless sensor networks must also take into account the ever-changing topology of the sensor network due to node failure and redistribution.

Since sensor nodes are usually operated by batteries and left unattended after deployment, power saving is a critical issue in WSNs. Many research efforts in the recent years have focused on developing power saving schemes for wireless sensor networks. These schemes include power saving hardware design, power saving topology design (Salhieh et al. 2001; Chakrabarti et al. 2003), power-efficient MAC layer protocols (Ye et al. 2002; Zheng et al. 2005; Rajendran et al. 2006; Pang et al. 2012) and network layer routing protocols (Sohrabi et al. 2000; Akkaya and Younis 2005). Designing power efficient MAC protocols is one of the techniques that prolong the lifetime of the network. In addition to energy efficiency, latency and throughput are also important features for consideration in MAC protocol design for WSNs. Commercial standards like IEEE 802.11 have a power management scheme for ad hoc networks, wherein the nodes remain in idle listening state at low traffic to conserve power, significant power is wasted even in the idle listening mode. Hence, IEEE 802.11 is not suitable for sensor networks. A properly designed MAC protocol allows the nodes to access the channel in a way that saves energy and support QoS.

## 2.4 Network Layer

The network layer in a WSN must be designed with typical considerations in mind, ever existing power efficiency, WSNs are data-centric networks, and WSNs have attribute-based addressing and location awareness. The link layer handles how two nodes talk to each other, while the network layer is responsible for deciding which node to talk to.

The simplest design is flooding. When using flooding, each node receiving data repeats it by broadcasting the data to every neighbor unless the max hop lifetime of the data has been reached or the receiving node is the destination. The major support for flooding is the simplicity. It requires no costly topology maintenance or complex route discovery. The shortcomings, however, are substantial:

- Implosion, it occurs when two nodes (A and B) share multiple (*n*) neighbors. Node A will broadcast data to all *n* of these neighbors. Node B will then receive a copy of the data from each of them.
- Overlap, when two nodes share the same sensing region. If a stimulus occurs within this overlap, both nodes will report it.
- The last and most crucial problem is resource blindness. Flooding does not take into account available energy resources.

Gossiping is an enhancement to flooding. In gossiping, when a node receives data, it randomly chooses a neighbor and sends the data to it. Gossiping avoids the problem of implosion, but does not address the other two concerns and contributes to the latency of the network.

A step up from flooding and gossiping is ideal dissemination. In this algorithm, data is sent along a shortest-path route from the originating node. Such approach guarantees that every node will receive every piece of information exactly once. No energy is wasted in sending or receiving redundant data. However, the overhead involved in keeping track of the shortest paths is substantial. Also, ideal dissemination does not take into account that some node may not need a particular piece of information; nor does it allow for resource awareness.

A little more sophisticated family of protocols is sensor protocols for information via negotiation (SPIN). The SPIN family addresses the deficiencies of classic flooding by negotiation and resource adaptation. With more sophisticated and energy aware techniques for data dissemination, it reduces the amount of energy expended, solves the problems of implosion, overlap, and resource blindness, and ensures that only interested nodes will expend energy to receive data (Kulik et al. 2002; Rehena et al. 2011). Negotiation helps to overcome the problems of implosion and overlap and ensures only useful and desired information is disseminated. In order for negotiation to work, nodes must describe the data to be sent using meta-data. In order for SPIN to be efficient the meta-data must be significantly shorter than the data being described. Also, meta-data describing two distinguishable pieces of data must be different. Likewise, if two pieces of data are indistinguishable, they will share the same meta-data. The format of the meta-data is not specified by SPIN, but rather application specific.

SPIN-2 is an implementation of SPIN that employs a low-energy threshold. When energy is abundant, the node functions as normal. However, when the resource manager detects that a node power supply is reaching the low-energy threshold, the node will not participate in later stages of the protocol. This prolongs the life of the node and allows it to perform only high priority functions.

SPIN is a more sophisticated and energy aware schema for data dissemination. It reduces the amount of energy expended, solves the problems implosion of, overlap, and resource blindness, and ensures that only interested nodes will expend energy to receive data.

## 2.5 Transport Layer

Transport control protocol for WSNs should account for several concerns (Wang et al. 2005):

- Congestion control and reliability. The more data streams flow from sensor nodes to sinks in WSNs, the more congestion might occur around sinks. Also there are some high-bandwidth data streams produced by multi-media sensors. Therefore it is necessary to design effective congestion detection, congestion avoidance, and congestion control mechanisms for WSNs. Although MAC protocol can recover packets loss from bit-error, it has no way to handle packets loss from buffer overflow. Then the transport protocol for WSNs should have mechanism for packets loss recovery such as ACK and Selective ACK as used in TCP protocol so as to guarantee reliability.
  Reliability under WSNs may have different meaning from traditional networks that generally guarantee correct transmission of every packet. For some application, WSNs only need to correctly receive packets from a certain area, not from every sensor nodes in this area, or may be contempt with some ratio of successful transmission from a sensor node. These modified reliability concept motivates the design of different transport control protocols. It would be better to use hop-by-hop mechanism for congestion control and loss recovery since it can reduce packet dropping and conserve energy. The hop-by-hop mechanism can simultaneously lower buffer requirement at intermediate nodes, which suits the limited memory sensor nodes.
- Simplifying initial connecting process or use connectionless protocol so as to speedup start and guarantee throughput and lower transmission delay. Most of applications in WSNs are reactive, that is passively monitor and wait for event occurring before reporting to sink. These applications may have only few packets for each reporting, and the simple and short initial setup process is more effective and efficient.
- Avoiding packets dropping as possible to lessen energy wastage. In order to avoid packet dropping, the transport protocol can use active congestion control at the cost of a lower link utility. The active congestion control (ACC) can trigger congestion avoidance before congestion occurs. An example of ACC is to make sender (or intermediate nodes) reduce sending (or forwarding) rate when the buffer size of their downstream neighbors overruns a threshold.
- Guaranteeing fairness for different sensor nodes so that each sensor node can achieve a fair throughput. Otherwise the loaded sensor nodes cannot properly report events in their area, which leads to erroneous monitoring, tracking, and control.
- Enabling cross-layer interaction. If a routing algorithm can notify route failure to the transport protocol, the transport protocol will know that packet loss is not from congestion but from route failure, and consequently the sender will regulate its current sending rate to guarantee high throughput and low delay.

Chapter 4 of this book exhaustively considers transport control protocols for WSNs.

## 2.6 Application Layer

To address application layer protocols it is primordial to address some functions that are to be implemented, specifically, data fusion and management, clock synchronization, and positioning. A WSN is intended to be deployed in environments where sensors can be exposed to circumstances that might interfere with provided measurements. Such circumstances include strong variations of pressure, temperature, radiation, and electromagnetic noise. Thus, measurements may be imprecise in such scenarios. *Data fusion* is used to overcome sensor failures, technological limitations, and spatial and temporal coverage problems. Data fusion is generally defined as the use of techniques that combine data from multiple sources and gather this information in order to achieve inferences, which will be more efficient and potentially more accurate than if they were achieved by means of a single source. The term efficient, in this case, can mean more reliable delivery of accurate information, more complete, and more dependable. The data fusion can be implemented in both centralized and distributed systems. In a centralized system, all raw sensor data would be sent to one node, and the data fusion would all occur at the same location. In a distributed system, the different fusion modules would be implemented on distributed components (Abdelgawad and Bayoumi 2012).

Communications in wireless sensor networks are data-centric, with the objective of delivering collected data in a timely fashion. Also, such networks are resource-constrained, in terms of sensor nodes'processing power, communication bandwidth, storage space and energy. This gives rise to new face-offs in information processing and data management in wireless sensor networks. In-network data processing techniques, from simple reporting to more complicated collective communications, such as data aggregation, broadcast, multicast and gossip, are challenging. On the other hand, data collected by sensors can intrinsically be viewed as signals. By exploiting signal processing techniques, collective communications can be done in more energy-efficient ways. Several work deal with data management, (Xu et al. 2009) investigate in-network query processing strategies for K nearest neighbor (KNN) queries in location aware wireless sensor networks. Also, (Brayne et al. 2008) propose an adaptive query processing mechanism to dynamically adjust query processing in wireless sensor networks. Moreover, (Akcan and Brönnimann 2007) develop a distributed, weighted sampling algorithm to sample sensing data to reduce energy consumption. By exploring the adaptive model selection algorithms, (Le Borgne et al. 2007) derive an adaptive, lightweight and on-line algorithm for prediction sensing data.

Sensed data is of limited usage if it is not accompanied by the coordinates of the sensor position and a time stamp, this is a primary motive for *clock synchronization* in WSNs. Data fusion is a prime function that depends also on clock synchronization. For instance, a vehicle going through acoustic sensors can be detected, throughout its path, by different sensor nodes at different moments. A fusion node receiving the raw information from the sensor nodes can refine it by estimating the speed and the direction of the sensed vehicle. For this application, among others, synchronized timestamps together with position information are essential. Also, WSNs are expected to have very small form factors and be cheap such that they can be deployed in very large numbers. Once deployed, WSNs are usually unattended, so battery replacement is impractical, but since they are typically expected to work for extended periods of time, there is no better way to conserve energy but to put the nodes to sleep and to wake up at the same time to be able to exchange information. Clock synchronization in WSNs is the subject of extensive work (Elson and Römer 2003; Sundararaman et al. 2005; Sun et al. 2006; Sommer and Wattenhofer 2009; Wu et al. 2011).

*Positioning*, knowledge of the position of the sensing nodes in a WSN is an essential part of many sensor network operations and applications. Sensors reporting monitored data need to also report the location where the information is sensed, and hence, sensors need to be aware of their position. In addition, many network protocols such as routing require location information in order to provide the specific protocol service. WSNs may be deployed in hostile environments where malicious adversaries attempt to spoof the locations of the sensors by attacking the localization process. For example, an attacker may alter the distance estimations of a sensor to several reference points, or replay beacons from one part of the network to some distant part of the network, thus providing false localization information. Hence, there is a need to ensure that the location estimation is performed in a robust way, even in the presence of attacks. Furthermore, adversaries can compromise the untethered sensor devices and force them to report a false location to the data collection points. Therefore, a secure positioning system must have a mechanism to verify the location claim of any sensor. Positioning in WSN is a topic of extensive research, leading to numerous positioning systems that provide an estimation of the sensor location (Lazos et al. 2005; Akkaya et al. 2007; Kim et al. 2007; Tennina et al. 2008; Younis and Akkaya 2008; Tennina et al. 2009).

System administrators interact with WSNs sensor management protocol (SMP). Unlike many other networks, WSNs consist of nodes that do not have global IDs, and they are usually infra-structureless. Therefore, SMP needs to access the nodes by using attribute-based naming and location-based addressing. SMP is a management protocol that provides the software operation needed to perform several administrative tasks (Akyildiz et al. 2002):

- Introducing to the sensor nodes the rules related to data aggregation, attribute-based naming, and clustering.
- Exchanging data related to the location finding algorithms.
- Time synchronization of the sensor nodes.
- Moving sensor nodes.
- Turning sensor nodes on and off.
- Querying the sensor network configuration and the status of nodes, and re-configuring the sensor network.

- Authentication, key distribution and security in data communications.

## 2.7 Cross-Layer Protocols for WSNs

The severe energy constraints of battery-powered sensor nodes necessitate energy-efficient communication protocols in order to fulfill the application objectives of WSNs. It is much more resource-efficient, according to some research, to have a unified scheme which melts common protocol layer functionalities into a cross-layer module for resource-constrained sensor nodes. A unified cross-layer communication protocol, for efficient and reliable event communication, considers the effects on WSNs of replacing transport, routing, medium access functionalities, and physical layers (wireless channel).

A unified cross-layering is such that both the information and the functionalities of traditional communication layers are melted in a single protocol. The objective of the proposed cross-layer protocol is highly reliable communication with minimal energy consumption, adaptive communication decisions and local congestion avoidance. Protocol operation is governed by the concept of initiative determination. Based on this concept, the cross-layer protocol performs received based contention, local congestion control, and distributed duty cycle operation in order to realize efficient and reliable communication in WSN. Performance evaluation reveals that the proposed cross-layer protocol significantly improves the communication efficiency and outperforms the traditional layered protocol architectures (Akyildiz et al. 2006).

## 2.8 Conclusion for Continuation

Several considerations must be taken when developing protocols for wireless sensor networks. Traditional thinking where the focus is on quality of service is somehow revised. In WSNs, QoS is compromised to conserve energy and preserve the life of the network. WSNs are a kind of "totalitarian" system, every one is for the good of all, no individualism, the whole network must survive even at the expense of falling sensors. Concern must be accorded at every level of the protocol stack to conserve energy, and to allow individual nodes to reconfigure the network and modify their set of tasks according to the resources available.

The protocol stack for WSNs consists of five standard protocol layers trimmed to satisfy typical sensors features, namely, application layer, transport layer, network layer, data-link layer, and physical layer. These layers address network dynamics and energy efficiency. Functions such as localization, coverage, storage, synchronization, security, and data aggregation and compression are network services that enable proper sensors functioning. Implementation of WSNs protocols at different layers in the protocol stack aims at minimizing energy consumption, and end-to-end delay, and maintaining system efficiency. Traditional networking protocols are not designed to meet these WSNs requirements, hence, new energy-efficient protocols have been proposed for all layers of the protocol stack. These protocols employ cross-layer optimization by supporting interactions across the protocol layers. Specifically, protocol state information at a particular layer is shared across all the layers to meet the specific requirements of the WSN.

As sensor nodes operate on limited battery power, energy usage is a very important concern in a WSN; and there has been significant research focus that revolves around harvesting and energy conservation by minimizing energy consumption. When a sensor node is depleted of energy, it will fade out and disengage from the network, which may significantly impact the performance of the application. Sensor network lifetime depends on the number of active nodes and network connectivity, so energy must be used efficiently in order to maximize the network lifetime.

Energy harvesting involves nodes replenishing their energy from an energy source (Gilbert and Balouchi 2008; Galperti and Alippi 2008; Seah et al. 2009; Vullers et al. 2010). Potential energy sources include solar cells (Hande et al. 2007), vibration (Lei and Yuan 2008), fuel cells, acoustic noise, and a mobile supplier such as a robot to replenish energy. The robots charge themselves with energy and then deliver energy to the nodes.

Energy conservation in a WSN maximizes network lifetime and is addressed through efficient reliable wireless communication, smart sensor placement to achieve adequate coverage, security and efficient storage management, and data aggregation and data compression. Such approaches satisfy both the energy constraint and provide QoS. For reliable communication, services such as congestion control, active buffer monitoring, acknowledgements, and packet-loss recovery are necessary to guarantee packet delivery. Communication strength depends on the placement of sensor nodes. Sparse sensor placement may result in long-range transmission and higher energy usage, while dense sensor placement may result in short-range transmission and less energy consumption. Coverage is interrelated to sensor placement. The total number of sensors in the network and their placement determine the degree of network coverage. Depending on the application, a higher degree of coverage may be required to increase the accuracy of the sensed data.

One for all, and all for all, that is the main objective of all layers in the WSNs protocol stack.

## 2.9 Exercises

1. Define protocol.
2. What are the considerations and concerns of the WSNs protocol stack?
3. Elaborate on the physical layer for WSNs typical features.
4. How is the data link layer for WSNs different?

5. Explain how is the network layer in WSNs different.
6. What is positioning and clock synchronization?
7. How is data fusion crucial in WSNs?
8. What is the importance of data aggregation for WSNs?
9. Determine the functions of the transport layer in WSNs.
10. How does the typical usage of WSNs affect the application layer?

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