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Transformations of Large Technical Systems

A Multilevel Analysis of the Dutch Highway System (1950–2000)

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The transformation of existing systems is an underexposed topic in large technical systems (LTS) research. Most LTS research has focused on the emergence and stabilization of systems, ending with momentum. But how is momentum overcome, and how do transformations come about? This article presents a multilevel perspective to understand such transformations, using insights from STS and evolutionary economics. The multilevel perspective is illustrated with a longitudinal case study of the Dutch highway system (1950 to 2000).

Keywords: *transitions; large technical systems; multilevel perspective; highway system*

The study of large technical systems (LTS) is a fascinating research stream within science and technology studies (Hughes 1983; Mayntz and Hughes 1988; La Porte 1991; Summerton 1994; Coutard 1999). LTS researchers focus on infrastructural networks, which stretch geographical areas (e.g., electricity systems, railroad networks, telephone networks). LTS researchers have also developed a particular mode of analysis, looking at seamless webs and sociotechnical linkages (Hughes 1986, 1987). System builders, such as Edison in the case of electricity systems, not only work on technical artifacts but also on people, texts, regulations, markets, and so on. These elements have to be articulated and aligned if the sociotechnical system as a whole is to work. This theoretical approach is agency oriented, looking at (inter)actions of social groups and actors.

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Established large technical systems are argued to have “momentum” (Hughes 1994). This term comes from physics, referring to the quantity of motion that an object has. The higher its momentum, the more an object will continue along its trajectory. Hughes does not see momentum as a physical property of large technical systems but as result of stabilizing connections between technology and society. The emergence and development of large technical systems can be conceptualized as a life cycle with several phases, for example, invention, development, innovation, growth, competition, consolidation, and momentum (Hughes 1987). Momentum is the end stage in which technical systems have become embedded in society, resulting in many linkages between firms, regulatory bodies, departments in educational institutions, and research laboratories. Furthermore, people adapt their lifestyles to artifacts, new infrastructures are created, and industrial supply chains emerge (Hughes 1994). In the momentum stage, large technical systems possess direction and display a rate of growth that suggests velocity. This momentum and directionality are not autonomous but stem from the alignments of many social and technical elements.

This view also applies to technological trajectories. Evolutionary economists argue for the existence of “natural trajectories” in technical communities (Nelson and Winter 1982, 258). Sociologists of technology agree that technical activities in local practices can add up to technological trajectories at a global level but disagree with the prefix *natural*. MacKenzie (1992) argued: “a technological trajectory can be seen as a self-fulfilling prophecy. Persistent patterns of technological change are persistent, because technologists and others believe they will be persistent” (p. 32). So technologies develop along trajectories because engineers share cognitive rules (ideas, perceptions, beliefs, expectations) that guide their activities in certain directions. Trajectories are not natural but performed. Hughes would add that trajectories are not only stabilized by beliefs but also by social and technical linkages, vested interests, regulations, infrastructures, and so on.

LTS researchers have conceptualized the emergence and stabilization of technical systems, resulting in momentum. But they have given less attention to how momentum and stability are overcome. The research question in this article is: how do major changes occur in *existing* large technical systems?

Summerton (1994) recognized the lack of attention for system changes in the LTS literature. She argued: “systems and networks are dynamic entities. They can seldom be black-boxed for good” (p. 5). Previously achieved closure is undone when linkages between elements of the system begin to weaken, opening up the potential for change. Although Summerton does not delve into the precise dynamics of transformation, she notes several

circumstances that are important for the opening up of systems: (1) the presence of underlying problems within the system and actors' view of these problems; (2) problems external to the system, such as environmental impacts and risks and concerns about safety (concern about externalities is often expressed as consumer pressure, public protest, and regulatory pressure); (3) changing competitive conditions (to defend and expand their markets, system builders may change the strategic course of development); (4) political developments or contingencies in an even broader sense (e.g., war or threat of war); and (5) changes in cultural values and broad political ideologies.

Staudenmaier (1989) also drew attention to the decline stage of systems, proposing to analyze it as a weakening of the linkages between technology and the wider context: "As new political priorities, shifting demographics, changing tastes, ecological transformations, or competing actors come to the fore, the sweet fit between context and technology that characterized the momentum stage begins to unravel" (p. 155).

So Staudenmaier and Summerton see changes in external circumstances as important for changes in LTS. But such external changes are not sufficient for major changes. The link between external circumstances and actors needs to be further conceptualized to understand change processes (something to which Summerton's explication alluded). This conceptual need is expressed more broadly in science and technology studies. Many STS approaches (actor-network theory, LTS) have a strong focus on actors, local practices, heterogeneity, and contingency. These actor-oriented approaches have been criticized for a tendency toward voluntarism and heroic storylines and a neglect of the influence of wider social structures, shared cognitive repertoires, and power (Russell 1986; Williams and Edge 1996). Macro-approaches, on the other hand, assume too much rationality and too many linear mechanisms through which external factors influence technological development. Sørensen and Levold (1992) diagnosed this dichotomy of conceptual approaches that focus either on individual companies and scientists (e.g., Pasteur, Edison) or on macro-structures such as the economy or the government. Hence, they argued for the importance of "paying attention to the meso-level . . . and institutional aspects of technological innovation" (p. 21). Misa (1994) also reviewed micro and macro approaches, arguing that "macro studies tend to abstract from individual case studies, to impute rationality on actor's behalfs or posit functionality for their actions, and to be order driven. . . . Micro studies tend to focus solely on case studies, to refute rationality . . . and functionality, and be disorder-respecting" (p. 119). To overcome this dichotomy, Misa (pp. 140–41) suggested: "a focus on meso-level institutions and organisations that mediate between the individual

and the cosmos . . . offers a framework for integrating the social shaping of technology and the technological shaping of society.” So within STS, there is a call for multilevel approaches.¹

This article answers that call and also addresses the topic of system changes. It proposes a multilevel perspective on transitions from one system to another. This perspective distinguishes three conceptual levels: a “niche” level in which radical novelties emerge, a “regime” level that refers to cognitive rules shared in social networks related to the existing system, and a “landscape” level that refers to exogenous developments. The main point is that transitions come about through alignments between processes at these different levels. The multilevel perspective has been applied mainly to radical innovations that *substitute* existing technical systems. So the perspective is implicitly based on the radical-incremental dichotomy, distinguishing between innovations that proceed along an established trajectory and radical shifts to a new trajectory. Although both types of changes occur, they do not cover all possible changes. This article proposes that changes in the direction of *existing* trajectories constitute another change process. Building on Van de Poel (2000, 2003), this process, which unfolds from within, is called transformation. Transformation is particularly relevant for large technical systems, which are characterized by deep-sunk investments and momentum.²

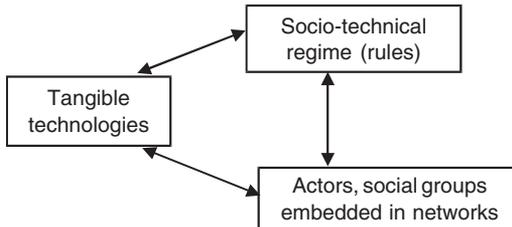
In sum, the article has several aims. First, it draws attention to the topic of major changes in existing systems. Second, a multilevel perspective is described to understand major system changes and to articulate a possible combination of micro-meso-macro approaches in technology studies. Third, this multilevel perspective is refined to understand transformation as special type of change process, with shifts in direction of technical trajectories.

The second section of the article describes the multilevel perspective and makes conceptual additions to understand transformations in large technical systems. The third section illustrates this perspective with a longitudinal case study of the Dutch highway system (1950 to 2000). The fourth section analyzes the case and draws conclusions.

Conceptual Multilevel Perspective on Transitions and Transformations

The multilevel perspective (MLP) emerged at the crossroads of evolutionary economics and STS and was developed by scholars bridging both disciplines (Rip and Kemp 1998; Kemp, Schot, and Hoogma 1998; Kemp, Rip,

Figure 1
Three Interrelated Dimensions in Sociotechnical Systems



Source: Geels (2004, p. 903).

and Schot 2001; Geels 2002, 2004, 2005a). The MLP has evolutionary characteristics but is elaborated sociologically and institutionally.

The meso-level is formed by sociotechnical regimes, the institutional structures that link technical artifacts and actors. Although sociotechnical systems are seamless configurations of elements, an analytical distinction is made between three interrelated dimensions: (1) tangible technologies, for example, artefacts, devices, and infrastructures; (2) actors and social groups who develop, use, maintain, and regulate technologies; and (3) rules (understood as regimes) that guide perceptions and activities of actors and social groups (Figure 1).

Actors in social groups do not act autonomously but in the context of social networks and sociotechnical regimes. Nelson and Winter (1982) coined the term *technological regime*, which refers to the cognitive routines (e.g., search heuristics) that are shared in a community of engineers, guiding their R&D activities. Through their coordinative effects, technological regimes create relative stability at the sectoral level and lead to incremental innovation along technical trajectories. Rip and Kemp (1998) widened the definition of *technological regimes* to the sociological category of “rules”:

A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures. (p. 340)

Elaborating on this definition, Geels (2004) distinguished formal, normative, and cognitive rules. Formal rules are standards, government regulations,

and so on. Normative rules are sense of identity, behavioral norms, role expectations, and so on. Examples of cognitive rules are guiding principles, goals, search heuristics, problem agendas, and rules of thumb. The different rules do not exist individually but are linked together in semicoherent sets of rules, called regimes. Shared rules coordinate and guide action but, following Giddens's structuration theory, are also reproduced and changed through action. While *technological regimes* refers to communities of engineers, the functioning of sociotechnical systems involves more social groups, for example, scientists, users, policy makers, and special-interest groups. These social groups interact and form networks with mutual dependencies. The intergroup coordination is represented with the concept of *sociotechnical regimes* (Geels 2004).

Regime rules account for the stability and momentum of existing sociotechnical systems. Cognitive routines make engineers and designers look in particular directions, blinding them to developments outside their focus (Nelson and Winter 1982). Legally binding contracts, technical standards, or rules for government subsidies may favor existing technologies (Walker 2000). Organizations are resistant to major changes because they develop "webs of interdependent relationships with buyers, suppliers, and financial backers . . . and patterns of culture, norms and ideology" (Tushman and Romanelli 1985, 177). Industries may create professional associations or branch organizations to do political lobbying on their behalf (Unruh 2000). As a result of these mechanisms, existing sociotechnical systems are dynamically stable: innovation still occurs but is of an incremental nature, leading to cumulative technical trajectories.

Radical innovations usually emerge outside or on the fringe of existing regimes. New technologies emerge as "hopeful monstrosities" (Mokyr 1990, 291). They are "hopeful" because product champions believe in a promising future. But they are "monstrous" because their price/performance characteristics are low, so they cannot survive on mainstream markets. Radical novelties initially need protection and nurturing. Using an ecological metaphor, this early protection comes from niches. Evolutionary economists highlight small *market niches*, in which selection criteria are different from the existing regime and commercial transactions provide a trickle of resources for reproduction (Saviotti 1996). Sociologists of technology also distinguish *technological niches*, in which public subsidies enable networks of actors to work on new technologies (Schot, Hoogma, and Elzen 1994; Kemp, Schot, and Hoogma 1998; Kemp, Rip, and Schot 2001; Hoogma et al. 2002). The three analytical dimensions (technologies, actors, rules) also apply to niche

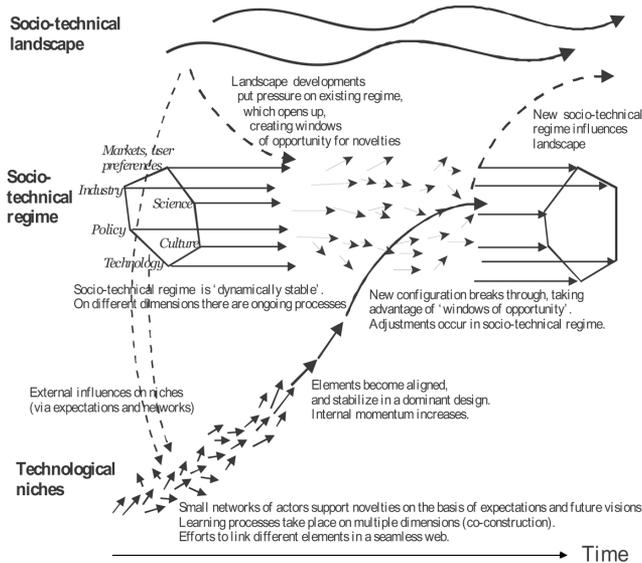
innovations. The difference with regimes is that the networks of actors that carry niche innovations are small and precarious, rules are vague and diffuse, and technologies are unstable. There is much “interpretative flexibility” about technical and functional characteristics, about problems, solutions, and meanings of the artifact (Bijker 1995, 73). The sociological niche literature identified important processes in niches: the building of social networks that carry, nurture, and develop novelties; heterogeneous learning processes to improve performance and build a working sociotechnical configuration; and articulation of expectations and visions to guide learning processes and attract attention and funding. Pilot and demonstration projects form good locations for these processes because they enable interactions between users, policy makers, firms, and engineers.

The macro-level is formed by the sociotechnical landscape, which refers to aspects of the wider exogenous environment, for example, globalization, environmental problems, and cultural changes (Rip and Kemp 1998).³ The metaphor *landscape* is used because of the literal connotation of relative “hardness” and to include the material aspects of society, for example, material and spatial arrangements of cities, factories, and electricity infrastructures. The landscape forms gradients for action, which are beyond the direct influence of regime and niche actors.

The (socio)logic of these three levels is that they provide increasing degrees of coordination and structuration of activities in local practices. The rules in technological niches are vague and imprecise, providing only loose structuration. Actors need to put in a lot of work to uphold the niche. In sociotechnical regimes, coordination is stronger. Actors in local practices can deviate from regime rules, but this is difficult and takes much effort. Sociotechnical landscapes are hard to deviate from, providing even stronger structuration.

With these concepts, the MLP conceptualizes transitions as follows. When a radical innovation emerges in a niche, there is much uncertainty and flux (characterized by small, diverging arrows in Figure 2). Social networks and visions in niches are influenced by ongoing dynamics at regime and landscape levels. For instance, product champions promise that niche innovations may solve problems in the existing regime. However, as long as existing regimes are stable, novelties have little chance to break through and remain stuck in niches. Because of stabilizing mechanisms, existing trajectories in sociotechnical regimes continue through incremental innovations (represented with straight arrows in Figure 2). At some point in time, landscape changes may occur, for example, emergence of new values, changes in macro-political

Figure 2
Multilevel Perspective on Transitions



Source: Adapted from Geels (2002, 1263).

coalitions, wars, and so on. These landscape changes are similar to the external circumstances mentioned by Staudenmaier and Summerton. Such external changes may create pressure on the existing regime, leading to tensions and changes in regime rules: (1) internal technical problems may be perceived as insurmountable, (2) negative externalities may lead to criticism and societal protest, (3) user preferences and markets may change, and (4) new regulations may be formulated that introduce performance standards that cannot be met by the existing technology. Pressures and rule changes may cause de-alignment of the existing regime, creating windows of opportunity for broader change (represented in Figure 2 with diverging arrows at the regime level). If niche innovations have sufficiently stabilized and experienced price/performance improvements, they may take advantage of these opportunities and diffuse more widely. The breakthrough in mainstream markets leads to competition with the existing technology. This competition is played out in

markets but also with regard to regulations, infrastructure investments, user practices, and so on. If the novelty wins the competition, technological substitution is accompanied by broader sociotechnical changes. The societal embedding of a new system may, over time, also contribute to broader landscape changes.

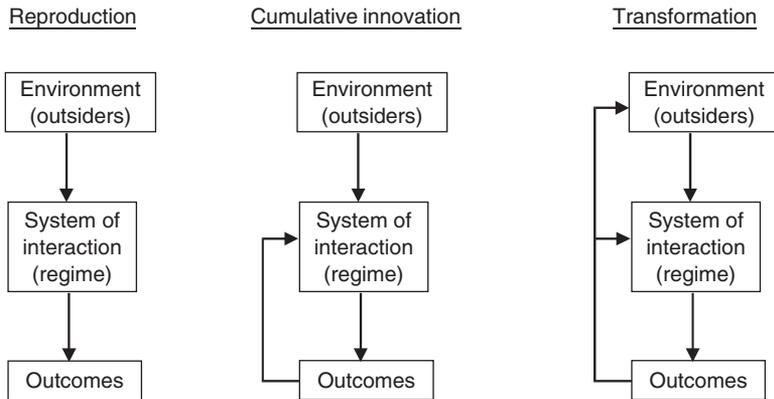
An important aspect of the MLP is to do away with linear causality. There is no simple cause or driver in transitions. Instead, there are processes at multiple dimensions and levels simultaneously. Transitions come about when these processes link up and reinforce each other. To understand major system changes, one should analyze both the regime level (actors, technologies, and rules) and influences from landscape and niche levels.

The MLP has been illustrated with case studies of historical transitions, for example, from sailing ships to steamships (Geels 2002), from manual unloading of ships to pneumatic elevators (Van Driel and Schot 2005), from pumps and wells to piped water systems (Geels 2005b). It should be noted, however, that the representation in Figure 2 and the case studies have a bias toward technological substitution, focusing on the emergence of a major innovation that subsequently breaks through and substitutes the existing regime.

This article proposes that major system changes may also result from changes in the *direction* of existing trajectories. The understanding of this transformation process requires some conceptual additions to the MLP. These additions will also bring actors more explicitly into the MLP. The MLP, as described above, is a structuralist process perspective that works from the outside in, offering an abstract explanation in terms of alignments between multiple processes. But since these processes are enacted by actors, the MLP also has an inside-out dimension (although this is not immediately visible in Figure 2). While converging processes may create windows of opportunity, these windows have to be used by actors. So, precise explanations of system changes depend on a combination of multilevel linkages and agency.

Transformation means that the new grows out of the old. The existing technical system is not replaced but changed from within through cumulative adjustments in new directions. To further conceptualize this transformation process, Van de Poel's (2000, 2003) sociological framework is used. This framework comprises three elements: (1) the system of interaction, which refers to the social network and the rules that guide activities of regime insiders; (2) outcomes produced by regime actors, for example, technical artifacts and environmental effects; and (3) the environment, which is made up of outsiders, that is, actors excluded from the regime. Different feedbacks between these elements result in three types of change processes: reproduction, cumulative innovation, and transformation (Figure 3).

Figure 3
Typology of Change Processes in Existing Technical Systems



Source: Van de Poel (2000, 388), Boudon (1981). From *Technology Analysis & Strategic Management*, 12, 383-397. <http://www.tandf.co.uk/journals>. Used with permission of Taylor & Francis, Ltd.

In reproduction, there is no feedback from outcomes to regime or environment. Rules of the existing regime are reproduced precisely, and innovation is absent. This process is hardly relevant for technological change. In cumulative innovation, outcomes are fed back to the system of interaction, leading to minor rules changes in the regime and incremental innovation. This process lies behind the stable regime trajectories in Figure 2. In transformation, outcomes are fed back to the system of interaction and to outsiders. When outsiders are concerned about negative outcomes, they voice criticism. This feedback from outsiders may lead to substantial changes in regime rules and reorientation of the innovation trajectory.

Outsider groups need not be present from the start but may emerge gradually in response to negative effects. Van de Poel (2000) distinguishes three outsider groups who influence regimes through different mechanisms. First, *societal pressure groups* influence regimes through mobilizing public opinion. Their protest may influence policy makers and lead to tougher regulations. Second, *outside professional scientists or engineers* may possess knowledge that allows them to criticize technical details of regimes. These outsiders can influence regimes by acquiring roles as insiders and bringing

in new knowledge. Third, *outsider firms and entrepreneurs* can influence regimes by developing new technologies that can compete with the existing system.

With three additions and reformulations, this framework can be combined with the MLP. First, while Van de Poel's emphasis on insider-outsider interaction is useful, his direct arrows in Figure 3 suggest that protests from outsiders immediately influence actions of regime insiders. But regime insiders usually shield themselves from criticism, excluding or ignoring outsiders. Hence, outsiders' influence on regime rules is better viewed as contested and involving power struggles. The second reformulation is to make a distinction between outsiders and a wider exogenous environment. While insider-outsider interactions take place at the regime level, they are influenced by broader developments at the sociotechnical landscape level. These landscape developments may enhance or weaken the relative power of outsider groups, exacerbate regime problems, and change political rules of the game. The third reformulation is to link technology development by outsider firms to niche innovations. In the MLP, niches form spaces in which radical novelties are developed by actors who deviate from regime rules (such as outside firms). The MLP, as described above, implicitly assumes that niche innovations are competitive to the existing system. But following Van de Poel (2003), it is also possible that new technologies have symbiotic relationships and are adopted in the system.

Using these additions and reformulations, system transformation is enacted at the regime level of the MLP. When there is no protest from outsiders, developments proceed incrementally along trajectories. This changes when external landscape developments create pressure on the system and when outsider groups voice criticism about negative side effects. Regime insiders may neglect and ignore pressures and criticisms, or they can react to them. This depends on strategic games and power struggles, which may be influenced by external landscape changes. Transformation occurs when regime insiders change regime rules that influence the direction of innovation and development trajectories (e.g., goals, search heuristics, guiding principles). However, a single rule change may have only limited transformational effects because regimes are semicoherent sets of rules. The influence of a rule change depends on the degree to which other regime rules are also changed. Regime actors may concede changes in peripheral rules but leave core rules intact. Particular rule changes can be neutralized if regime actors resist further translation to other rules. So there is much scope for strategic maneuvering and struggling.

The above description of the transformation process only involves landscape and regime levels. If outsider firms are present that develop niche innovations, then the third level in the MLP may also be involved in transformation processes. Symbiotic niche innovations may be adopted in the system to solve particular problems. But once adopted, learning processes with new technologies may change ideas and lead to further transformation.

The Transformation of the Dutch Highway System (1950 to 2000)⁴

The multilevel perspective on transformation will be illustrated with a longitudinal case study of the Dutch highway system. This large technical system gained momentum in the 1950s and 1960s but came under fire from outsider protest groups in the 1970s. This led to several rule changes (e.g., in values, goals, and guiding principles of transport policy), but transformational effects were limited. In the 1990s, transport telematics and traffic management formed the seeds for a transformation process that is still unfolding. The differences between the 1970s and 1990s will be explained in the fourth section of the article with the conceptual perspective. In three subsections, the case study describes technologies, rules, and interactions between relevant social groups, situated in broader landscape developments. The focus is on aggregate and long-term patterns, not on individual actors and day-to-day interactions.

Emerging Momentum (1950 to 1970)

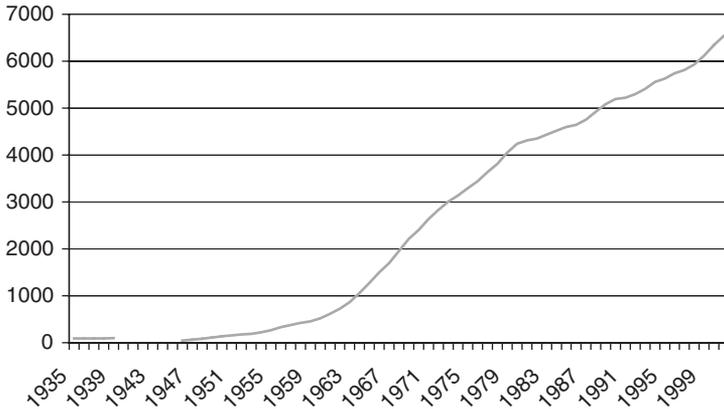
Postwar expansion of the highway system built on several prewar developments. A powerful road lobby had emerged in the 1920s, involving the Royal Institute of Engineers, the automobile user representation group ANWB (initially a bicycle club), and the Royal Dutch Automobile Club (KNAC). This lobby supported the first National Road Plan (1927), in which the government envisaged 2,800 kilometers of primary roads. Rijkswaterstaat (RWS), the engineering and building department of the Ministry of Traffic and Transport, would implement this plan. The plan involved building new roads and upgrading existing roads, many of which were unpaved or had brick pavement. For primary road pavement, there were two competing technical options: concrete and synthetic asphalt. To develop technoscientific knowledge about chemical properties of both pavements, RWS created specialist engineering departments, for instance,

the National Road Building Laboratory (1927). Learning also occurred through concrete implementation projects. By 1940, the primary road network had several pavements: 41 percent asphalt, 18 percent concrete, 35 percent bricks, and 6 percent other materials (Mom 2004). The growing dominance of asphalt was accompanied by stabilizing design rules (quality norms, test regulations, road building requirements), codified by RWS and distributed to road builders. The production of asphalt roads was a craft-based process. Asphalt was produced on-site, transported with wheelbarrows, and spread out on foundations with rubber brooms. Steamrollers then pressed the material together (Thedinga 1972). As contractor and supervisor of road-building projects, RWS developed close ties with road builders and the road lobby.

The Second World War created enormous damage to existing infrastructures. The Road Fund, implemented in 1927 to coordinate funding for road building from the Road Tax Law, was canceled, and the money was used for repair of war damages (Ligtermoet 1990). The American Marshall Plan (1948 to 1952) created some financial resources for road infrastructures and also provided new guiding principles for highway design, in particular, efficiency, large-scale solutions, and a scientific approach. But the financial basis for road-building projects remained small in the 1950s. After the flood disaster of 1953, killing eighteen hundred people, most national resources went to the Deltaplan. Because of lacking resources, the *National Road Plan* (1958) offered little new prospect (Ligtermoet 1990).

Despite the absence of grand visions, technical learning and articulation continued. For asphalt pavements, the quality standards, preparation recipes, and measuring methods were further refined, leading to a stable technical regime. As road builders switched from manual to mechanical production methods, these regime rules were embodied in road-building machines. Mechanization and scale increases in road building improved efficiency from 1 man-hour per square meter before the war to 0.1 man-hour per square meter in 1970 (Thedinga 1972). Major changes also occurred in the thinking and expertise at RWS. Highway engineers went to the United States for study trips and were inspired by the American highway system. While engineers used to see the national road network as connections between separate roads that ended in cities, they increasingly approached it as a highway *system* in which flow and efficiency were crucial. In this system approach, nodes and traffic junctions became important design topics. Extensive design studies were made of roundabouts, traffic circles, and flyovers (e.g., cloverleaves, windmills). Reconstruction projects in Rotterdam, which had been heavily bombed

Figure 4
Number of Cars in the Netherlands, in Thousands

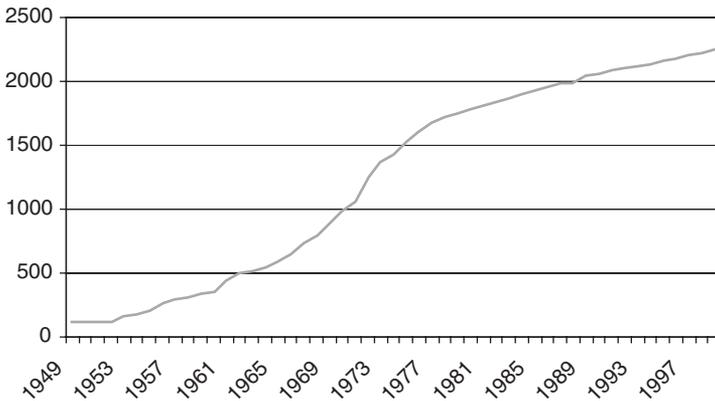


Source: Bovag/RAI (2001, 69).

during the war, provided real-world testing grounds for the new design ideas (Provoost 1996). America was also an exemplar for the application of science to transport topics, especially the forecasting and management of traffic flows. Traffic science emerged as a new discipline in the Netherlands in the 1950s, promoted and developed by RWS. The automobile club ANWB created a new magazine, *Verkeerskunde* (Traffic Science), in 1950, and conferences were organized to stimulate knowledge development. The new discipline addressed topics such as road density per area, efficient road network design, and the psychology of the driver. But the topic that received most attention was the forecasting of future road densities (Van der Ham 1999). The ambition was to use traffic forecasts for scientific underpinnings of national road plans. Until 1960, these forecasts were based on trend extrapolations from traffic counts. After 1960, it was tried to capture traffic flows in mathematical equations, to be used in integrated traffic models (Beukers 1978).

The low rate of road building in the 1950s was increasingly criticized by car-user organizations such as the KNAC and ANWB. Societal pressure further increased in the 1960s as economic growth enabled more people to buy cars (Figure 4). Economic growth also generated more tax incomes, creating space for the installation of a new National Road Fund in 1965.

Figure 5
Length of Highway Roads (in km)



Source: Central Bureau of Statistics (www.cbs.nl), accessed 16 December 2005.

With more resources available, the *Structural Scheme for the National Road Network* (1966) articulated an ambitious new vision. It aimed to facilitate mobility growth by a tremendous expansion of the primary road network, to eventually fifty-three hundred kilometers. This implied the creation of thirty-two hundred kilometers of new roads (Ligtermoet 1990). Using traffic forecasting models, future flows were calculated using projected population densities. These calculations then determined the width and shape of roads. The plan was presented as a technocratic endeavor, based on scientific considerations. The new mode of systems thinking was visible because in the plan, roads no longer ended in cities but crossed and connected outside cities. So the highway system acquired a reality, independent of cities (Provoost 1996). The new vision was embedded in the *National Road Plan* (1968), which accelerated highway construction (Figure 5).

Government and Parliament left the making of road plans and highway designs to RWS. This organization possessed the competencies in traffic forecasting, pavement technology, crossovers, and systems thinking. RWS enjoyed great societal prestige because of its achievements in postwar reconstruction projects. So it seemed natural that RWS would also build the nation's highway system. RWS had a political and societal mandate for this

task. So, by 1970, the highway system had acquired momentum, with RWS as influential spider in the social web. RWS had centralized and accumulated technical knowledge; it had strong social ties; and its engineering vision of motorization and highway expansion was widely shared by Parliament, Ministries, the highway lobby, and citizens.

Outsider Protest and Reactions (1970 to 1990)

But in the early 1970s, major landscape changes created pressure on the highway system. One major change was the increasing concern about environmental problems. This value change was stimulated by environmental scandals in the chemical industry and books such as *A Blueprint for Survival* (1972) and *The Limits to Growth* (1972). A second society-wide change was emancipation of citizens, who demanded more voice in decision-making processes. Government policies were no longer taken for granted. In the Netherlands, this led to institutional changes in procedures for decision making, giving citizens and societal groups more participatory power.

These landscape changes resulted in several rule changes in the highway regime. These rule changes were negotiated and enacted in an ongoing game that involved new actors who criticized the highway regime as outsider groups. In this game, actors reacted to each other, and in doing so, altered some of the regime rules. There were four rounds of rule changes that cumulatively pointed in the direction of substantial transformations in the highway system. But the transformational effects were moderated in a fifth round, which left important core rules intact.

1. New groups emerged, articulating worries about environmental and social effects of cars and highways. Protest groups such as Stop the Child Killing placed safety concerns on the agenda, while the First Dutch Cyclist Union drew attention to the decline of urban life and environmental problems. These groups were outsiders that tried to get negative side effects on the agenda of regime actors.
2. In 1970 and 1974, formal procedures for decision making on road plans were changed to increase participatory opportunities for citizens and special-interest groups. Highway engineers had to make intended road designs publicly available as the basis for public hearings in which actors could express their opinions. If actors suggested alternative routes, highway engineers had to investigate them and discuss results in new hearings. The next step was that intended road plans were discussed in city councils to incorporate them in local spatial plans for which municipalities were responsible. These new procedures gave citizens and societal

groups substantial power to influence decision making (Huberts 1988). During the hearing phase they could propose many alternative plans and to city councils they could submit written objections, thus delaying decisions for a long time.

3. Escalating protests against a particular road-building project damaged the public image of RWS. Because road A-27 was planned to cut through a forest on the estate Amelisweerd, environmental protests were mounted. Students from the action group Amelisweerd proposed alternative routes that were less damaging to the forest, which were dismissed by RWS (Grimbergen, Huibers, and Van der Peijl 1983). RWS tried to overrule the protests and alternatives with traffic-science arguments: if the A-27 was not built or if a different route was followed, bottlenecks would arise elsewhere in the highway system. Local environmental arguments were thus overruled with system logic and traffic science. The conflict received much attention in the media. In 1971, with the eyes of the nation on it, the Utrecht city council chose one of the alternative routes, against the RWS' advice. This was a victory for the environmental-protest groups. In 1975, the conflict was revitalized. To reduce traffic noise levels in Amelisweerd forest, RWS engineers wanted to construct a deepened road. But environmental groups were concerned about possible effects on groundwater levels and vegetation. Eventually, protesters occupied the forest to protect it. The struggle escalated in 1982 when the military police used much force to evacuate the forest. This led to public outrage, and RWS came to be seen as an arrogant bully, a technocratic organization that pushed through its plans at any price. This negative symbolic meaning eroded the legitimacy and societal mandate of RWS.
4. To address environmental and other traffic problems, politicians began formulating new goals for transport policy: slowing down car diffusion and stimulating public transport to facilitate a "modal shift" (from private to public transport modes). Hence, financial contributions to road building were reduced, and motor vehicle taxes were increased (Ligtermoet 1990). Politicians also emphasized the embedding of roads in the natural landscape and quality of life in cities, summarized as "LNC values" (landscape, nature, cultural heritage).
5. Although politicians were firm in public debates, they paid less attention to the actual translation of new goals into real policy instruments. This allowed RWS and the Ministry of Traffic and Transport to pay only lip service to the new goals. Although RWS created a subdepartment for aesthetic design, to accommodate LNC values, it was small and mainly served to "sex up" design works. Furthermore, the transport minister was hesitant to implement tough instruments. In a draft for the *Long-Term Plan Personal Mobility* (1976 to 1980), civil servants proposed sharp measures to slow down the growth of car traffic. But Minister Westerterp

did not adopt the proposals, for fear of public protest from car owners, car lobby organizations, and conservative political parties (Van der Ham 1999). Hence, the *First Structural Plan for Traffic and Transport* (1977) was a paper exercise that formulated ambitious goals but no accompanying policy instruments (Ligtermoet 1990). The ministry argued that little was known about the precise effects of mobility-limiting instruments and that more research was needed (Ligtermoet 1990). This accelerated the development of complicated computer models and large databases within RWS, with the promise of being able to calculate effects of policy instruments on traffic flows and car adoption (Beukers 1978).

In sum, the limited translation into policy instruments during this fifth round moderated the transformational effect of the other rule changes in the highway regime. Hence, highway construction continued in the 1970s, reaching its highest speed in terms of new kilometers per year (Figure 5). Because of lengthy decision-making processes, road construction in the 1970s carried out plans that had been approved in the 1960s. In the second half of the 1970s, the speed of highway construction began to slow down as a result of cutbacks on road-building budgets (Van der Ham 1999). This was a change in speed, not in direction.

Policy evaluations in the 1980s showed that the *First Structural Plan for Traffic and Transport* (1977) had not achieved its goals. Furthermore, traffic jams appeared as a new problem on the policy agenda. An influential McKinsey report, *Settling Accounts with Traffic Jams* (1986), calculated that thirty-three million hours per year were lost in traffic jams, costing 682 million guilders (three hundred million euro; Van der Ham 1999). The *Second Structural Plan for Traffic and Transport* (1988) made an attempt to develop an integral policy that addressed congestion, accessibility, and quality-of-life issues (safety, environment, landscape). The plan proposed to improve public transport and remove bottlenecks in the highway system. The plan also contained two innovative proposals for transformation. One proposal was to build transferia, that is, transfer places that linked public and private transport. Using the highway system, people would drive to transferia, where they parked their car and used upgraded public transport systems to reach their urban destination. This idea no longer saw highways and public transport as competing systems but linked them together. A second innovative proposal was road pricing, which implied a transformation because highways would no longer be “free” but would function as a market in which drivers paid directly for what they used (Ligtermoet 1990). Although the *Second Structural Plan* had high integral ambitions and innovative proposals, it was not very concrete. The transferia proposal faced many practical problems in

linking public and private transport and was not implemented. With regard to road pricing, the Ministry of Traffic and Transport started a project in the early 1990s. But it failed because of strong societal opposition from right-wing political parties (VVD), newspapers (*Telegraaf*), and the car-lobby organization ANWB.

Dynamic Traffic Management and Participatory Decision Making (1990 to 2000)

In the 1990s, the economic importance of infrastructures rose on the political agenda. The transport lobby gave infrastructures positive symbolic meanings with metaphors such as *Netherlands Distribution Country* and *mainports* (Rotterdam, Schiphol). New plans were made for substantial investments in infrastructure projects, for example, the Second Maasport in Rotterdam harbor, High Speed Trains, Betuwe train (to Germany), and a fifth landing strip at Schiphol airport. But these infrastructure projects encountered much societal protest from local residents and environmental groups. To handle protests, new ideas about participatory decision making were embraced by planners and policy makers. Stakeholders should be included in project design in an early stage to express their problem definitions and suggestions. Several advantages were claimed for participatory processes. By incorporating societal groups and citizens, they would be less likely to protest in a later stage. Participatory processes would also create more support for the plans. And third, citizens and societal groups could bring in specific local knowledge, making such processes more innovative. Within RWS, a special program, InfraLab (1994 to 1997), was set up to experiment with participatory processes in infrastructure projects. *Ex post* evaluations showed that stakeholders were happy about the process and felt taken seriously, often leading to support for plans. But the innovativeness of participative projects was limited. It was found that projects were often more about process than about content, giving limited attention to rich and powerful solutions (Woltjer 2000; Van Zuylen 1997, 1999). Furthermore, the carryover effect to general policy discussions was limited. Interactive decision-making processes often occurred parallel to existing decision-making arenas, with limited interaction (Edelenbos 2000). Although participatory processes formed a new practice in the road-building regime, they functioned mostly as a management tool to facilitate the implementation of particular projects.

Another rule change in the 1990s was disillusionment about the effects of public transport on car use. Investments in public transport had risen from

300 million guilders (140 million euro) in 1986 to 2.25 billion guilders (1 billion euro) in 1997 (Ministry of Traffic and Transport 1999).⁵ But this did not lead to a modal shift from cars to public transport. In fact, the number of traffic jams increased 170 percent in the period from 1990 to 1998 (Ministry of Traffic and Transport 1999). The new perception among policy makers was that earlier policies had failed and were wrong. Hence, the ambitions to slow down car diffusion and facilitate a modal shift were abandoned. Accessibility and congestion became the most important issues in transport policy, prominently articulated in White Papers such as the *Long-Term Programme Infrastructure and Transport* (1995), *Working Together on Accessibility* (1996), and *Accessibility Offensive Randstad* (2000). In the *National Traffic and Transport Plan* (2000), a new principle was proclaimed: "Car driving is OK!" So, public transport was no longer seen as a substitute for the car.

Given the protests against infrastructure projects, accessibility and congestion could not be improved by simply building more roads. New roads could only be built where bottlenecks existed. Hence, a new guiding principle was developed in the highway regime: better use of existing roads. This led to new search heuristics, with innovative activities focusing on improving flows and the functioning of nodes (e.g., roundabouts, traffic circles, flyovers). But there was much uncertainty about how to achieve this. RWS engineers saw road pricing as a promising mechanism to improve traffic flows, but this instrument was politically unfeasible. Hence, the Transport Ministry and RWS tried a wide range of incremental innovations: (1) narrowing of traffic lanes so that more of them fit on a road, (2) use of hard shoulders during rush hour, (3) stimulation of teleworking to spread traffic flows during the day, (4) increase in the number of passengers per car (carpooling), and (5) bans for trucks to overtake other vehicles. The hope was that these incremental innovations might add up and have aggregate effects on traffic flows.

In the mid-1990s, a new technological niche emerged, piggybacking on the emergence of information and communication technologies. Around 1995, Dynamic Traffic Management (DTM) appeared in policy documents as a promising option to improve road use. New companies offered "smart" technologies, such as video cameras, magnetic road detectors, computer networks, communication technologies, and electronic signaling devices, that could be combined into DTM. So DTM existed as many technical configurations, for example, roadside-signaling systems (dynamic route information panels, dosage of highway entries, speed signaling), incident management (rapid reporting of accidents to prevent major traffic jams), vehicle control systems (intelligent cruise control, automatic guided vehicles, intelligent

speed adaptation), special group measures (extra lanes for freight transport or public transport), vehicle information systems (radio traffic information, computerized route-finding systems), and road-pricing systems.

Policy makers and highway engineers were enthusiastic about DTM because it promised to add intelligence to the highway system, allowing car drivers to circumvent traffic jams and allowing road planners to influence traffic flows. But the promise of DTM was diffuse, as was the variety of technical options. In the late 1990s, the Transport Ministry significantly invested in the RWS innovation program *Roads to the Future*. The promise of DTM was explored in concrete pilot projects about intelligent networks, dynamic road signals, automatic vehicle guidance, smart road surfaces, and traffic information systems. The *National Traffic and Transport Plan* (2000) articulated promises that DTM formed the core for future highway transformations resulting in less congestion and improved traffic flows.

The DTM niche may lead to transformations such as technical additions to the infrastructure (cameras, magnetic detection loops, electronic traffic signals), new roles for public policy (e.g., managers of traffic flows), and new user patterns (e.g., on-board computers, which provide information and assist the driver). Major effects are predicted by product champions and traffic engineers. Other experts warn against too-high expectations, arguing that DTM may increase road capacities (maybe even 20 to 30 percent) but that traffic jams will continue to exist because less congestion attracts new traffic (Van Zuylen 2000). Although the degree of highway transformation is still open to debate, money has been made available to develop and experiment with DTM. So a protected space has been created for innovative work and implementation. Its future effects depend on how actors will act on further technical developments.

Analysis and Conclusions

The research question was how do major changes occur in existing large technical systems? To answer that question, a multilevel perspective was described that conceptualizes major changes as outcome of alignments between processes at three different levels (niche, regime, landscape). This perspective links up with debates in STS about micro-, meso-, and macro-analyses of technological change. The multilevel perspective was previously developed to understand transitions from one sociotechnical system to another. This was implicitly based on the incremental-radical dichotomy, with processes either progressing cumulatively along trajectories or shifting

to entirely new trajectories. This article made an addition to the multilevel perspective by distinguishing transformation as particular change process, consisting of changing directions in trajectories. To understand this transformation process, the article built on Van de Poel's sociological framework that conceptualizes how actions of regime insiders produce effects to which outsiders may react. Outsiders' protests create pressure on the regime and may lead to rule changes. This usually involves contestation, power struggles, and willingness from regime insiders to change their practices. The dynamics of this regime-transformation process take place within broader developments at the sociotechnical landscape level. These wider developments may help get certain issues on the agenda and influence the relative power of outsider groups. Van de Poel distinguished three kinds of outsider groups: societal pressure groups, professional engineers, and outsider firms. The latter group, outsider firms, are important actors at the niche level, creating new technologies. If outsider firms and niche innovations are absent, only two levels (regime and landscape) are involved in transformations; if they are present, then three levels are involved.

The third section of the article illustrated the multilevel perspective on transformations with a longitudinal case study. While the main emphasis in the description was on dynamics at the regime level, external landscape developments were also important, for example, the Second World War, postwar reconstruction, rapid economic growth in the 1950s and 1960s, concerns about environmental problems and participation in the 1970s, and concerns about national competitiveness in the 1990s. Niche innovations came in during the 1990s, when dynamic traffic management facilitated a shift to enhanced use of existing roads and incorporation of smart technologies. So the three levels were visible in the case study.

Besides being descriptively useful, the multilevel perspective, combined with insider-outsider dynamics, also provides explanations. The case study described two periods in which major transformations were on the agenda, the 1970s and the 1990s. While transformational effects in the 1970s remained limited, they were more substantial in the 1990s. This difference can be explained.

In the 1970s, only two levels interacted. Concern about environmental problems and public participation were general *landscape* developments that affected the highway system. Pressure was enacted by new outsider groups, which placed negative side effects on the agenda (environment, safety, quality of life). In Van de Poel's terms, these outsiders were societal pressure groups, not professional engineers and outsider firms. The pressure led to several rule changes in the highway *regime*, for example, more

open procedures for decision making about highway routes, new policy goals (slowing down car diffusion, stimulation of public transport, more attention for LNC values), and a deterioration of the symbolic image of Rijkswaterstaat. However, the transformational effect of these rule changes remained limited because they were not translated into further changes in other rules of the highway regime. For instance, they were not translated into concrete policy instruments, and they did not lead to new search heuristics for traffic engineers and transport planners. A further explanation of this limited translation involves the structure of the social network. In the 1970s, this network was highly polarized between insiders and outsiders. The main insiders were highway engineers at Rijkswaterstaat, policy makers and planners at the Transport Ministry, and right-wing political parties that were probusiness and procar (VVD). These insiders were further supported by special-interest groups such as the transport lobby and the motorists organization ANWB. The main outsiders were green political parties, environmental organizations, green activists, and the Ministry of Environmental Affairs. The insider-outsider interactions were highly polarized and antagonistic in the 1970s. The outsiders were able to change several regime rules. But regime insiders felt attacked by these rule changes, which they saw as being imposed on them by irrational activists and media-sensitive politicians. Highway engineers and transport planners were not enthusiastic about the new political goals (less instead of more roads), which had few inspiring elements and few technical challenges for them. Hence, regime actors resisted the translation of rule changes to other regime rules. They paid lip service to the new goals and only made superficial changes such as creating an ineffective subdepartment for aesthetic design (to implement LNC values). So, despite landscape pressure and protests from societal-pressure groups, transformational effects were limited because regime insiders were able to neutralize rule changes.

In the 1990s, three levels interacted. At the *landscape* level, competitiveness was a macro-political concern that influenced thinking about highway systems. Special-interest groups such as the transport lobby and ANWB translated this concern in metaphors that emphasized the economic importance of highways. Hence, congestion and accessibility rapidly rose to prominence of the *regime* on the problem agenda. Outsiders were local residents and environmental groups protesting against big infrastructure projects. Regime insiders reacted to these protests by articulating a new practice: more public participation in decision making. But this practice was implemented as a management tool, not as a fundamentally different style of system building. More substantial rule changes in the regime

occurred in problem agendas, perceptions, guiding principles, and search heuristics. Congestion and accessibility rose to the top of the problem agenda. A change in perception was that modal shift (shifting people from cars to public transport) was no longer seen as an answer to these problems. Although car driving was politically and symbolically embraced again, there was limited space to build new roads. Hence, the new guiding principle was that existing roads should be better used by improving traffic flows. This was translated into new search heuristics for innovative activities, for example, improve the functioning of nodes in the network and a range of organizational innovations ranging from carpooling to the use of hard shoulders during rush hour. All these dynamics occurred through interactions between regime and landscape levels. Interaction with the third level in the MLP occurred when dynamic traffic management (DTM) appeared as an appealing *niche innovation* for regime insiders. Transport planners could present DTM as a possible solution to congestion problems (in public debate or in discussions with Parliament). And for RWS highway engineers, the application of information and communication technologies (ICT) to the highway system was an interesting technical challenge that appealed to their technical skills and interests. The DTM niche did not compete with the existing highway system but formed a symbiotic innovation that could be adopted to transform some of the regime's functionalities. Many traffic engineers felt that DTM could breathe new life in a highway system that threatened to become bogged down in congestion and public protests. The enthusiasm about the promise of DTM contributed to the willingness of regime insiders to embrace rule changes in the regime and actively contribute to their further translation to other rule changes. This was a major difference with the 1970s period. This difference can be reformulated as a hypothesis, namely that the interaction between *three* levels is more likely to result in transformation processes than is interaction between *two* levels. The argument would be that the presence of a promising niche innovation with technical potential makes regime insiders more willing to accept and implement rule changes in response to outside pressures.

The conclusion is that the multilevel perspective, complemented with insider-outsider dynamics, can describe and explain transformations in the Dutch highway system. This broadens the applicability and usefulness of the multilevel perspective, which has previously been applied to cases of technological substitution. This article demonstrated the perspective's usefulness for understanding transformations. But because this is based on a single case study, it is only a proof of principle. Further research on transformation is needed to claim broader generalizability.

Notes

1. I want to thank Mark Winskel for reminding me of this point.
2. Mokyr (1990) notes: "Dramatic sudden changes are not impossible in such systems, but are less likely because of the need to preserve compatibility with other components. Because of the resistance of other parts in the system, large changes were slow in the making" (p. 296).
3. The term *landscape* is also used in complexity theory (e.g., Kauffman 1995). The so-called "fitness landscape" indicates how an organism's evolutionary fitness changes when it innovates in particular directions. Fitness landscapes thus indicate how variations influence evolutionary survival (chance at selection). Being focused on selection, fitness landscapes include both external factors (e.g., climate and terrain in biological evolution; sociotechnical landscape in technological evolution) and competition with other organisms (e.g., predators in biology; firms and technologies at regime and niche level in technology). So, despite some similarities, fitness landscapes are not the same as sociotechnical landscapes.
4. The empirical description builds on a report written for Rijkswaterstaat (Geels, Disco, and Lintsen 2003).
5. Road building received 700 million guilders in 1986 and 1.5 billion guilders in 1997.

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