The evolution of ecodesign

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THE EVOLUTION OF ECODESIGN

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Abstract

Product designs evolve and change over long periods of time, through phases of experimentation, consolidation and maturity, followed by further innovation or by decline. The examples used to illustrate this process of evolution are innovations in environmentally responsible 'green' products (or ecodesigns) in the areas of bicycles, automobiles, housing, lighting, washing machines and wave energy technology. The article argues that, to have significant environmental benefits, such green products will have to evolve from experimental designs into mature products and outlines some of the factors affecting the rate and extent of ecodesign evolution.

1 Introduction

This article is concerned with the innovation and evolution of products designed to reduce environmental impacts - so-called 'green' products or ecodesigns. This, arguably, is one of most important areas of product design and technical innovation for the 1990s because of the growing environmental problems associated with industrial production and consumption, ranging from global and regional impacts such as climate change and acid rain to more local issues such as contaminated land and waste disposal [1]. Such environmental problems are beginning to have a major influence on the strategies of companies and the decisions of managers, designers and engineers.

Recent studies have shown that industry's responses to environmental problems is shaped by a number of factors [2, 3]. First, and most important, has been the introduction from the 1970s onwards of increasingly tough environmental regulation at national and regional (especially EC) levels. Second, there was the emergence in the late 1980s of a market sector of 'green' consumers wanting 'environmentally-friendly' products, plus some large retailers and manufacturers specifying less environmentally-damaging products, materials and components from their suppliers. Third, there was the realisation by some companies that cost savings could be made by introducing more energy efficient and less wasteful manufacturing processes and commercial advantages gained by developing greener products ahead of their competitors. Fourth, an increasing number of senior managers began to regard the environment as an area of corporate social responsibility or experienced pressures to improve environmental performance from employees, investors and shareholders.

Until quite recently industry's usual technical response to environmental problems has involved measures to reduce pollution and wastes *after* they have been produced; for example, by installing pollution control equipment on industrial plant or equipping cars with catalytic convertors. However, from the late 1980s onwards some companies gradually began to shift their attention from such 'end of pipe' approaches back up the production chain towards the source of environmental emissions. Initially the focus was mainly on 'cleaner' manufacturing processes, which generate less pollution and waste or make more efficient use of energy and materials. Then, with the growing understanding that environmental emissions are generated by the use and disposal of a product as well as by its manufacture, attention began to turn to the design of 'greener' products.

Examining the beginnings of this shift of industry towards ecodesign is part of the research programme of the Design Innovation Group (DIG) at the Open University. In a recent DIG study managers and designers, in companies in the UK, the USA and Australia that have developed and marketed 'greener' products, were interviewed to obtain information on their reasons for undertaking an ecodesign project, the research, design and development processes involved, and the commercial outcomes [4].

One of the outputs of this research programme is the development of case studies of innovative green products. The cases include both what have been described as 'incremental' green products, which are designed to reduce one or two specific environmental problems (e.g low CFC refrigerators to limit ozone depletion), and 'systematic' ecodesigns (e.g compact fluorescent lamps), which attempt to take account of all environmental impacts throughout the product life-cycle from initial manufacture to final disposal [5]. Table 1 shows another way of categorising these greener products, in this case by their principal environmental focus (or objective) and design approach.

[Table 1 near here]

Our study indicates that green product development can be commercially very successful for the innovating firms. For example, the introduction of a system for collecting and remanufacturing laser printer toner cartridges, to a quality equal or better than that of a new cartridge, has generated new business worth some £1.5 m/year for Getstetner, Australasia. The profits on the sales repaid the total initial investment in the project in less than one year and gave the company confidence to expand its 'Boomerang' toner cartridge remanufacturing facility.

The study also provides some support for the view that companies which fail to design or redesign their products to reduce environmental impacts will increasingly lose their competitive edge to more environmentally-conscious companies [6, 7, 8]. However, the research also shows that many green products are being developed by innovative small firms who can only have a relatively small impact on the market, and that companies generally only develop such products if this coincides with existing commercial objectives [9]. Thus, in many markets, there is still a long way to go before ecodesigns seriously challenge 'mainstream' products.

This article therefore attempts to set ecodesign in a wider context of technical change and design evolution. It argues that products designed to reduce environmental impact will have to develop and evolve over a long period of time before they are adopted widely enough to have a significant beneficial effect on the environment.

1.1 Patterns of innovation

A number of theorists in the fields of design, innovation and technical change have shown that successful products, technologies and industries evolve over time through a recognisable set of phases [10, 11, 12].

The evolutionary process starts with what may be called an *exploration* phase in which a variety of inventions and experimental designs are conceived and developed. This is typically followed by a phase of *consolidation* during which a limited range of 'dominant' designs are established [13, 14]. These dominant designs, together with their associated production processes, define a particular technological 'regime' or 'trajectory' [15, 16]. This is followed by a *mature* phase in which a range of standardised products are produced efficiently and diffused widely into society. In this phase the emphasis typically shifts from product innovation to innovation in production processes [13] with design and minor improvement innovations used to differentiate between rival manufacturers' products. As competition intensifies between mature products within the technological regime or trajectory, there usually emerges a phase of further product *innovation* and development of product *families* to capture new markets [17]. Finally, as the particular type of product reaches its limits of performance, it may *decline* and be *displaced* by products based on a new concept or technology [18], thus beginning the evolutionary process once again (see Figure 1).

[Figure 1 near here]

Until recently the evolution of products has been driven by the desire of inventors, designers and manufacturers to improve product performance and quality and/or to reduce production costs without consideration of the environmental consequences, other than those controlled by existing regulations. Ecodesign - meaning the design of artefacts which generate fewer adverse environmental impacts during all, or parts of, their total lifecycle from initial manufacture to final disposal - is therefore a relatively new concept. It follows that most ecodesigns are still located in the initial exploration phase of their evolution, with a few having moved into the consolidation phase. Those greener products that are reaching maturity tend to be modifications of existing dominant designs rather than new ecodesign concepts. If ecodesigns are to have a significant effect in reducing environmental problems, many more will have to evolve into the mature phase and be produced and used as widely as the conventional commodity products of today. This evolution of ecodesigns, from ideas and experiments to general acceptance, is likely to be a long process whose rate and direction is dependent on many technical, commercial, market and socio-political factors. Some of these stimulating and inhibiting factors are discussed in the Conclusions section of this article.

All this can be made clearer by considering a product which has already gone through such an evolution. This product, the bicycle, happens to be one of the earliest and best examples of ecodesign, although it was not originally conceived as such. The bicycle is by far the most energy efficient form of transport yet invented, consuming 40-100 times less primary energy per passenger km. than a car, 30-70 times less than a train, and 12-25 times less than a bus [19]. In addition the source of this energy is biological and hence renewable.

1.2 Evolution of the bicycle

Figure 2 is a diagrammatic overview of cycle design evolution based on earlier work by the author [20, 21]. It shows the various phases involved in the development of this successful artefact from its origins in the steerable 'hobby-horse' of the early 19th Century to the sophisticated competition machines of today.

[Figure 2 near here]

The exploration phase started with the invention in 1818 of the key concept - a steerable, human-propelled machine on which the rider balanced. This original machine had many drawbacks and so soon disappeared. But after some other early experiments, such as Macmillan's lever-driven bicycle, the invention around 1860 of the *Velocipede*, the first pedal and crank driven bicycle, initiated a phase of frantic design activity, component innovation and experimentation all directed at producing faster, safer, more comfortable and efficient cycles. The result was a huge variety of designs, including cycles with one, two, three, four or more wheels, which were direct-driven, lever-driven, chain-driven; front-steered, rear-steered, and so on. Figure 2 shows only a small selection of the main types. Within 30 years, however, this variety of designs had almost completely been displaced by convergence onto one 'dominant' design - the familiar diamond frame, rear chain-driven bicycle of the late 1880s. When equipped with pneumatic tyres (patented in 1888) this design created a boom in demand in the 1890s, when a craze for cycling spread through the middle and upper classes and to women as well as men.

Following the establishment of this dominant design, the mature phase of bicycle evolution involved much incremental improvement and innovation in materials, components and accessories - alloy steel and aluminium frames, derailleur gears, battery lights and so on. At the same time attention turned to innovation in the production technologies involved in manufacturing bicycles in order to make them at a price affordable to the ordinary person. There was, in other words, a shift from *product* to *process* innovation, bicycles became one of the first mass-produced consumer products, and firms like Raleigh grew to meet the demand. This pattern remains until today in countries like India and China where the majority of the world's bicycles, very similar to the 1890s machines, are manufactured.

However, by the 1960s in the advanced industrialised countries the bicycle had almost been displaced by other forms of transport, notably the car. The bicycle's revival depended partly on a move into the next phase of evolution, namely the development of a family of new designs to meet the wants of different markets - small wheel bicycles, 'fun' bicycles for children, folding bicycles, streamlined 'recumbent' cycles and so on. The introduction of the mountain bicycle to the mass market in the 1980s created another boom in demand, with more bicycles than automobiles sold annually in many developed countries. Modern bicycles include highly sophisticated designs with frames and components made from advanced aerospace materials, including titanium, carbon fibre and metal-matrix composites, and bicycle design and component manufacture is now often carried out utilising the latest computer aids and robotic technology.

The bicycle is probably the only example of an ecodesign that has gone through all the phases of evolution described earlier and is still developing and improving. The main barriers to its wider use are not the design of the bicycle itself, but lack of cycle facilities, safety problems and of course the dominance of the automobile.

1.3 A greener car?

The automobile itself is becoming 'greener' as the dominant design established in the 1930s - the four-wheeled machine with internal combustion engine and pressed steel, monocoque body - is being modified and challenged in response to growing environmental regulation [22]. However, the evolution of a greener automobile displays a wide variety of approaches and experiments by different manufacturers, designers and engineers typical of the early exploratory phase of ecodesign [23]. These range from incremental changes, such as the introduction of water-based paint coatings and recyclable plastics components, through a variety of new electric car designs using available battery technology (Figure 3), to radical new designs and technologies such as the proposed 'ultralight' car with a carbon fibre composite body and hybrid electric/internal combustion engine offering fuel economies two to ten times better than that of current designs [24].

[Figure 3 near here]

2 Examples of ecodesign evolution

Some areas of ecodesign are at a more highly evolved stage than the 'greener' automobile. In this section, therefore, some other examples of attempts at ecodesign will be examined to see how far they have moved along the evolutionary path.

Many of these examples are of product innovations whose design is focused on reducing fossil fuel consumption, but some also address the other main foci for ecodesign listed in Table 1; namely reduced natural resource consumption and reduced environmentally harmful emissions [25].

2.1 Low energy housing

Housing designed to minimise consumption of non-renewable fossil fuels was one of the earliest areas of ecodesign and has moved well beyond the initial exploration stage. Many traditional house forms were designed to minimise heating or cooling requirements, as well as being constructed from local and renewable materials. In this century early experiments include the solar house built at MIT in 1939. Since then many thousands of low energy houses have been designed and built in different countries. These have involved a variety of technical approaches: heavy insulation, passive solar gain, active solar heating, mechanical ventilation and heat recovery, interseasonal heat storage, and so on.

Since the early 1970s low energy house design has evolved, even in the relatively non energy-conscious UK, from the pioneering ideas and experiments of a few environmentally-aware alternative technologists and architects [26] to a 'demonstration' phase of trials and public displays of one-off designs. For example, Figure 4 shows one of a group of twelve experimental passive solar heated houses, with photovoltaic cells on the roof of the conservatory for generating electricity, built in 1986 for exhibition called 'Energy World' in Milton Keynes (a new urban settlement near London).

Since then, in the UK, low energy housing has further evolved from demonstration designs to the first commercial developments for sale on the general market. For example, Figure 5 shows a low energy design built in some numbers in the early 1990s. It is very well insulated and oriented for maximum passive solar gain, but also has active solar air heating with mechanical ventilation and heat recovery.

[Figures 4 and 5 near here]

In countries like Scandinavia and Canada low energy housing, designed and built to considerably higher performance standards than in the UK, are commonplace and even available as standard kits of parts for export. In the mid 1980s a group of twelve super-insulated timber frame houses were erected in Milton Keynes from kit of parts supplied by a Finnish firm. They are so well insulated that almost all space heating for these houses is provided by incidental heat gains from cooking, lighting, etc.

Low energy housing has therefore begun to move from the exploration phase into the consolidation phase of ecodesign evolution and in a few countries it has almost become a mature technology. Low energy housing is thus now more a matter of transfering the technology and adapting available designs to local conditions than basic invention and innovation.

2.2 Low energy lighting

Domestic electric lighting is dominated by incandescent lamps, which were invented in the 19th century and first introduced with tungsten filaments in 1909. Gas discharge lamps (fluorescent tubes) were introduced by General Electric in 1939.

The problem with incandescent lamps is that they are very inefficient (only about 10% of the electricity consumed is converted to light) and so the oil crisis of 1973/74 stimulated a search by the major lighting manufacturers, with government encouragement, for more energy-efficient forms of electric lighting. This resulted in a number of innovations, notably the development of tungsten-halogen lighting (which is about twice as efficient as the ordinary tungsten filament lamp) and the compact fluorescent lamp (which is about five times as efficient).

In the UK two main types of compact fluorescent lamp (CFL) were introduced in the early 1980s for domestic and commercial markets. Thorn-EMI launched its '2D' lamp which comprises a novel flat folded-form light which plugs into a separate reusable ballast unit or special light fitting incorporating ballast circuitry (to control cuurent flow). Philips subsequently introduced a range of compact lamps with integral ballast which, although less efficient in use of materials, could more readily be used as direct replacements for conventional tungsten filament lamps.

Thorn's 2D design largely failed to catch on in the domestic market, partly because of its size and unusual form and partly because of its higher initial cost than a Philips lamp. Philips and other manufacturers continued development of their lamps to make them cheaper, less bulky and more efficient - for example, by introducing electronic ballast - and available in a wide range of forms and power outputs.

Nevertheless, because of their high first cost, by the early 1990s CFLs had only captured some 2% of sales (by volume) in the domestic market and had only achieved higher penetration when they were specially promoted or subsidised. For example, in the USA some electric utilities distribute CFLs free to customers as a more economic option to building new power stations. In one such scheme California Edison handed out nearly half a million energy efficient lamps to low income customers thus saving the need to build 8 megawatts of new generating capacity [27]. A similar 'demand side management' programme was introduced on a small scale in Britain for residents of Holy Island off North Wales. The regional electricity company, Manweb, offered its customers two CFLs for the price of two ordinary incandescent lamps as part of an energy conservation plan designed to avoid having to uprate the Island's power link to Anglesey.

Low energy lighting does more than just saving energy. The results of a Dutch study shows that, over the total life cycle, CFLs - mainly because they consume less fossil fuel derived electricity, but also because they last some eight times longer - produce only about 30% of the solid waste and about 20% of the air pollution of an incandescent lamp of same light output [28]. The need to compare the impact of a 'greener' product with conventional designs over the total life cycle from initial manufacture to final disposal is illustrated by the issue of mercury emissions. Mercury vapour is essential for the operation of a compact fluorescent lamp and thus caused concern about mercury pollution. Yet life cycle analysis showed that the total mercury emissions from manufacture and disposal of CFLs are less than than the mercury emissions resulting from the extra coal burned to power an equivalent incandescent lamp [28].

Technical development of low energy electric lighting continues with the introduction of innovations such as induction lamps (which produce light by converting mercury gas to plasma with electromagnetic waves). Such innovations in lighting technology are being developed both by major manufacturers and small firms. The smaller firms, however, are mainly contributing by designing light fittings specially suited to low energy lamps. Many of these designs, such as a low energy floodlamp (which is the subject of one of the DIG's green product case studies mentioned earlier [9]), are mainly aimed at the commercial market as this has been more receptive to the economics of low energy lighting systems.

Low energy lighting as an ecodesign product seems to have moved from the exploration into the consolidation phase of innovation with mass production of dominant designs by major manufacturers having commenced. However, the technology still awaits acceptance on a wide scale largely because of the higher initial cost relative to conventional lamps and a lack of appreciation by consumers of the whole life savings in energy and money that are possible. Government or other market intervention to reduce the first cost seems necessary to stimulate the rapid diffusion of low energy lighting.

2.3 'Greener' washing machines

A product where existing government intervention, in the form of environmental labelling, may produce a more rapid change in customer behaviour is washing machines.

The domestic washing machine is a mature product mass-produced in a limited range of standard forms by a few major manufacturers. However, in the mid 1980s a few manufacturers began to introduce environmental considerations into the design of their washing machines as part of their strategy of competing on quality rather than price [29]. The German firm AEG, in particular, introduced incremental innovations in the washing, rinsing and spinning stages of their machines aimed at reducing energy, water and detergent consumption. AEG claim that water consumption of their machines halved between 1975 and 1988 and energy consumption reduced by 60%. For the washing stage one of the most successful energy and water saving approaches has been the 'Jetsystem' introduced by Zanussi in 1986. The water is circulated to the top of the machine and sprayed down on the clothes instead of soaking them in the drum (Figure 6).

[Figure 6 near here]

AEG and Zanussi adopted a 'proactive' strategy in ecodesign in advance of official environmental incentives or regulation affecting washing machines. However, washing machines are one of the first product groups to be subject to EC 'eco-labelling'. Ecolabelling will inform consumers which manufacturers' products meet certain criteria for environmental impacts during the various stages of a product's life from original manufacture to final disposal. Like other categories of product to be considered for ecolabelling in Europe, washing machines were subjected to a life cycle analysis or 'ecobalance' study to assess a range of environmental impacts at the various stages [30]. This life cycle analysis showed that over 95% of the environmental impacts of washing machines (energy and water consumption, air and water pollution, solid waste emissions) occur during their *use* (see Figure 7).

[Figure 7 near here]

As the results of this life cycle analysis became known, most other European manufacturers began developing their own energy, water and detergent saving designs in anticipation of the eco-labelling scheme, which was eventually introduced for washing machines in mid 1993. Hoover, for example, in early 1993 launched a new range of machines which, by means some of simple design changes - such as a drum which scoops up water and showers it over the clothes - uses 31% less water and 40% less energy than previous models as well as minimising detergent loss. (These washing machines were the first products to be awarded an EC ecolabel.) In fact by 1992 virtually all European washing machine manufacturers were making 'green' claims, even though the (British) Consumers' Association found that some of the claims were rather dubious: one manufacturer claimed reduced energy and water use simply by increasing recommended wash loads without changing the machine's design [31]. In order to maintain a 'green' marketing advantage, firms such as Hoover and AEG turned their attention to what life cycle analysis has shown to be relatively insignificant aspects of the environmental impacts of washing machines, such as reducing the amount of materials used for packaging and recycling of plastic components at the end of the product's life.

Washing machines are an example of a product which reached maturity without environmental factors playing much part in design. A few manufacturers then attempted to differentiate their products from the competition by designing for improved energy efficiency, reduced resource consumption and less pollution. Under the influence of eco-labelling, or other environmental pressures on manufacturers, it seems likely that within a few years that all European washing machines, except perhaps the lowest priced, will incorporate such changes and will become the dominant design. However, there are still markets, such as the USA and Australia, where top-loading washing machines are popular. Top-loaders have been shown to generate considerably more environmental impacts over their life cycle than front-loading designs [32]. Such markets will take longer to shift to energy, water and detergent saving designs, even if environmental labelling or other government initiatives are in force. To gain further major environmental and competitive advantages when all washing machines have been 'greened', manufacturers would have to develop a radically new system of clothes cleaning: for example, one firm is experimenting with ultrasonic cleaning.

2.4 Wave power devices

The examples so far have been of individual products designed or redesigned to reduce environmental impacts. However, the greatest benefits are likely to come from the design of whole *systems* based on less environmentally damaging technologies and products [7]. Unfortunately changing whole systems is more difficult than individual products. An example is the use of renewable energy sources for electricity generation.

The 1973/74 oil crisis produced an upsurge of interest in renewable energy technologies. One of these technologies involved systems to extract power from ocean waves. Wave power technology is interesting because its evolution has involved a very large number of inventions and competing design concepts. There are over a thousand different proposals for utilising wave energy in the patent literature [33].

Figure 8 shows some of the basic types of wave energy convertor. These vary from simple devices which rely on an enclosed column of water moving with the waves to pump air through an electricity generating turbine (e.g Nos. 7, 8, 9), to complex systems such as the Salter 'Duck' (No. 5) which employ moving floats to pump fluid through turbines. However, despite this vast amount of inventive activity and design diversity, no wave energy device has so far gone beyond the prototype demonstration stage and most devices remain as paper designs and patents.

[Figure 8 near here]

Various reasons have been given for the failure of wave energy technology to develop beyond the exploration phase of technical and design evolution. These include the major engineering problems and costs involved in building practical wave power plants; lack of government funding to develop the technology; opposition from entrenched energy interests; and official distortions in the economics of wave power [34]. Nevertheless, the wave power example does show that unless an area of innovative ecodesign can overcome such barriers to innovation it will remain as an undeveloped set of ideas, inventions and prototypes with little immediate benefit to the environment.

Electricity-generating wind turbines, in contrast, are a more successful area of renewable energy technology with some 20,000 machines in commercial operation world-wide [35]. A number of factors lie behind the comparative success of wind power, but one factor has been the establishment of a dominant design, the horizontal rotor machine with two or three propeller-type blades mounted on a vertical tower. This configuration, based on detailed analytical and computational models as well as extensive experimental data, has displaced most of the alternative designs proposed or built by inventors and developers during the 1970s and 1980s and has begun to benefit from the economies of series production.

3 Conclusions

The examples given in this article show that successful innovative technologies and designs evolve through major phases of exploration, consolidation and maturity, which may be followed by further innovation, or decline.

The implications of this for the evolution of ecodesigns are important. First, to have a significant impact on environmental problems, innovative products designed or redesigned according to ecodesign principles will have to be produced and used on a large scale. Except where environmental objectives may be achieved by simple modifications of existing mature products with a rapid turnover, this is likely to take many years, initially to develop the technology, then to consolidate effective designs and establish a market, finally to mass-produce the products efficiently and to diffuse them widely.

Second, as was mentioned in section 1.1, the rate and extent to which ecodesigns evolve through the various evolutionary phases depends on many factors. There is not space to make a comprehensive list of these factors or discuss them in detail, but they include those outlined below.

'Technical' factors concerned with the nature of the technologies involved, such as:

- The complexity of the technology and the degree of innovation involved [36]. (In general the more complex the technology and radical the innovation, the longer it will take to evolve.)

- The knowledge base and technical/design expertise available to develop ecodesigns [37]. (One of the barriers to the development of ecodesigns is that engineers and designers often lack information on, for example, the environmental implications of materials choice.)

'Commercial' factors concerned with the decision-making criteria of innovating organisations, including:

- The risks involved and the investments required to make a commercial return. (For example, to reduce risk manufacturers tend to invest only in greener products which help achieve existing commercial objectives.)
- The prospects of establishing a strategic competitive advantage in the development, manufacture and sale of particular green products [39]. (This will depend on the potential for patent protection and the ease of imitation of proprietary designs.)

'Market' factors concerned with the attitudes and choices of purchasers and users, for example:

- The relative advantages and drawbacks of ecodesigns over competing products, in terms of performance and cost as well as environmental impacts [36]. (In general customers will not buy greener products if they perform poorly, look ugly or are too expensive.)
- The 'image' of greener products and their compatibility with the attitudes and values of potential customers [36]. (For example, although a majority of consumers maintain that they would prefer 'greener' cars, sales of small fuel-efficient automobiles have been limited due to dominant consumer preferences for increasing engine power and performance.)

'Socio-political' factors affecting the context of technical change, such as:

- The regulatory framework of environmental controls (e.g pollution legislation) and incentives (e.g Ecolabelling) either promoting or inhibiting the development and adoption of ecodesigns.
- The degree of public awareness, media and political concern, and pressure group activity, over particular environmental issues.

In Table 2 an attempt has been made to evaluate the ecodesign examples outlined in this article against the above stimulating and inhibiting factors in order to compare their potential for rapid evolution from experimental into mature products. Although the assessments given are inevitably uncertain, being based on subjective judgement and an incomplete set of factors, the table does help to explain why, for example, ‘greener' washing machines are likely to develop and diffuse more widely and quickly than wave energy technology. More generally this analysis indicates that the creation and evolution of ecodesigns is dependent on a number of inter-related factors and is not just the result of environmental regulation or other individual pressures.

[Table 2 near here]

Given the various inhibiting factors, it seems likely that progress in the development and adoption of many ecodesigns, such as greener cars, will be uneven and sometimes slow. Nevertheless, because of the stimuli for change, as the year 2000 approaches, a growing number of products and processes seem likely to be designed to minimise their total impact on the environment.

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