Applying sustainability criteria to the separate treatment question: Insights from the application of an information processing architecture

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1 Introduction

Any analysis that is genuinely concerned with sustainability must begin without prejudice as to where the best combination of technologies resides. This analysis uses an information processing structure (Structure) which has been argued in Chapman (2013) as a way of encapsulating Nature in our technologies. If these Structures are formulated without any technology-specific equations then the result is outside of all technologies, and the sustainability zeros can be applied without prejudice to assess any technology either current or not yet discovered. Using such a Structure, and the composition of each of the 3 waste streams, the separate treatment of these is explored by applying the sustainability zeros as a series of constraints – mass balance is a good starting point for this.

When these sustainability zeros are applied to the separate treatment question for water, energy and environmental discharges, each of them point to the need for consideration of the separate treatment of each waste stream in order to move towards more sustainable technologies for our faeces, urine and greywater.

In addition, these sustainability zeros can be used to derive a set of requirements that would need to be met by a technology in order for it to be able to claim to be sustainable. It is then shown that a simplified Information Processing Structure using a single substrate with a first-order microbial kinetic utilising a single electron acceptor captures the essential behaviour of the complex system underlying the treatment of our waste streams. This enables extension of the mathematics of the underlying Structure to enable useful social insights into technology choice – providing additional mechanisms by which sustainability considerations can influence social choice. Being based on mass balance then using the simplified Structure means that this analysis occurs outside of the 'industry'. Also use of mass balance means that this form of analysis can be applied to a number of different technologies in series or parallel.

2 Summary of related work

Part I of this series (Chapman, 2013) argued for the formation of an **Information Processing Architecture** (composed of mathematical Structure(s), the location of its boundaries, and the manner of human interaction with it) which holds representations of all the complexity of a system. However, with the amount of information present, methods that enable access to the *most relevant* parts of the complexity are necessary to enable better decision making. Consider the following summary of part I (the architecture - (Chapman, 2013)) and Part II (social interaction - (Chapman, 2014)):

- Information Processing Structures (Structures) are mathematical constructs which can be formulated such that only Nature is encapsulated within the Structure (by using only the fundamental laws and processes, microbial kinetics etc).

    - The manner of human interaction with the Structure and our response to the resulting information (which includes the technologies we build to house Nature) consequently provide mechanisms by which Nature can enter our deliberations with respect to technology choice.
    - Analysis boundaries can be drawn such that adverse impacts are included in the Architecture.
- Sustainability requires that the great cycles of Nature complete with minimum: water use, energy use, environmental impacts, and maximum recycle potential.
    - The minimums implicit in sustainability can be put to these Structures **before** they are used to generate technologies.
    - If these Structures encapsulate the mathematical form of Nature then the sustainability minimums can be applied via the mathematical procedure of minimisation; but also:
        - Zero is particularly useful for approaching a Structure due to its location on the measurement scale.
        - Any measurement of a technology's performance is experimental evidence of a particular solution of its underlying Structure(s) and this measurement will be a known distance from zero.
- Social/commercial processes generate technologies.
    - Using measurement, **all** technologies can be prioritised from zero.
- Information flows occur in both directions between commercial processes (manufacturing the technology) and the community (utilising the technology) – the information content and the manner of these flows can be influenced by reference to the underlying Structure(s) to move society towards better technologies.
- The formation of an information conduit is one way of facilitating this information flow for a particular use.

For this paper, the desirability of the separate treatment of the three waste streams is addressed by reference to the zeros of sustainability perfection. This question is analysed in the first instance by applying the sustainability zeros to: water use, energy, environmental discharges and pathogen reduction. Each of these lines of argument is then explored in more depth.

3 The sustainability zeros

To narrow the focus before approaching a Structure, begin with an overview of the consequences of these zeros for human faecal waste disposal:

- Zero water – eliminates the use of water as a flush. Greywater volumes are primarily influenced by personal habits (frequency of washing) rather than any technology (low volume: shower rose, washing machines etc) – a social issue rather than a technology issue.
- Zero energy – eliminates chemical and filtration technologies, severely limits aeration methods, and reduces transport distances to zero (eliminate pumps, etc). A second level of considerations arise here in that if energy is required then biological/solar sources are preferable to fossil fuel use, for example: solar evaporation of liquids, or mechanical movement by hand (or foot).
- Zero environmental discharges – can be equated to maximum recycle/reuse potential,
    - Nutrient levels differ between the three waste streams. Ease of recycle/reuse will be specific to each stream.

- Transport questions apply, such as distance and cost/unit of nutrient.
- For recycle potential a measure of nutrient density would be a useful predictor of efficacy.
- Reuse greywater to enable nutrient recovery before the water joins the global flows. Alternatively, direct waste-to-air options (evapo-transpiration) can be considered.

- Zero pathogens – while not a sustainability question it is an important criteria that any technology would need to satisfy.
    - Pathogens are primarily in the faeces.
    - Considering that the other sustainability criteria noted above would eliminate chemical and filtration technologies then the time: temperature considerations would need serious consideration.

A more formal exploration of the value of using the sustainability zeros is contained in (Chapman, 2015b).

3.1 Zero Water as a sustainability priority

Clearly the toilet flush would be the first technology to be replaced if zero water consumption was a priority – is the flush really necessary or are zero-flush technologies possible? Implicit in zero-flush is limited transport distance, which would require consideration of a different design of toilet; a design where treatment occurs on-site. This question could be resolved by taking the characteristics of each waste stream to a Structure to identify the **requirements** needing to be met by a technology that closes the great cycles of Nature without using water (further discussed in Section 4.1). This puts the information in a form that can be used by the engineering/commerce sectors.

In addition to the availability of suitable technologies is the more important consideration of the **desirability** of mixing the three waste streams.

To assist in these deliberations consider that microbial kinetics (a component of Nature encased within a Structure) constrains any technology to a minimum holding time for sufficient degradation to occur. When this necessary holding time is combined with input volumes (using mass balance laws), the size of the container is seen to scale for the volume of liquid and its organic load (Table 1).

Table 1 - Data from a variety of sources but mostly: Lindstrom[1] (1992) and Gotaas[2] (1956). Note there is a paucity of data on the BOD_5 of faeces and urine. The degradation times for a faeces/urine mix were determined with data from a Swedish study that used low flush toilets. The volumes needing storage is Q*time(90% BOD_{tot}). The all mixed data is a sum of the three contributions, while the sewerage volume is based on 50% of the flow being greywater (Feachem, Bradley, Garelick, & Mara, 1983, p. 18). The sewerage degradation time[3] is assumed to be the same as the greywater which is clearly incorrect as sewage is a mixture of all three and would have a degradation time somewhere between 5 and 20.

	Faeces	Urine	Greywater	All mixed (No flush)	Sewerage (includes flush)
Q ($L\ p^{-1}\ day^{-1}$)	0.135[2]	1.2[2]	121[1]	122.34	242
Dry Wt ($g\ p^{-1} day^{-1}$)	35-70[2]	50-70[2]	-		
BOD_5 ($g\ p^{-1} day^{-1}$)	-	-	25[1]		45
Degradation time 90% BOD_{tot} (days)	20[1]		5[1]		5[3]
Volume stored in this time ($L\ p^{-1}$)	2.7	24	605	631.7	1210
Surface area of this cubical container (m^2)	0.12	0.5	4.3	4.9	6.8
Size (m^2) with evapo-transpiration @ 10 mm d^{-1}		0.12			

The cost of the container is positively correlated to the materials required for its construction and consequently to the surface area of the container needed to hold the volumes (via the relationship between volume and the container's surface area[1]). A linkage is established therefore between the economic system and the underlying Structure(s) which is independent of incumbent technologies. Less materials are required if each of the waste streams is treated separately (Table 1), for which commercial processes would influence whether this would be done at a lower total cost.

Yet another form of information arises from a Structure when the local climate and its particular evapo-transpiration rate is used to evaporate the volume of urine. In this case the size of evaporator that is necessary is output. Rather than needing a cubical container with a surface area of .499 m^2 to store the liquid, an evaporator (if located in an area with a climate that enables an ET rate of 10 mm/day) only needs a surface area of 0.12 m^2 (Table 1). The volume needing to be stored is reduced as a part of the mass is removed by evaporation. Other considerations would be necessary before a useful technology was developed – such as odour control and allowance for low ET days, but the possible existence of the technology is inherent in a well constructed information processing architecture. Evapo-transpiration treatment systems have been proposed for the mixed waste streams, but these require large surface areas; however using evaporation for the low-volume urine component appears to be possible with a very compact technology.

The advantages of separate treatment of each waste stream are further accentuated when recycle potential and pathogen differences are taken into account (discussed below).

3.2 Zero environmental discharges (recycle/reuse) as a sustainability priority

Consider the change in focus for technology choice if recycle/reuse potential assumed high priority in terms of preferred technologies. Most of the nutrients in sewerage arise from the toilet (WHO, 2006), less than 10% of N and K are sourced from the greywater (slightly higher % of P if high phosphate detergents are used). However there are also significant variations between the quantities of nutrients in the two body excretions (Table 2) evidence of which is particularly useful considering that most of the pathogens occur in the faeces.

Table 2 – Macronutrient data for faeces and urine. Data from Table 1.1 (WHO, 2006, p. 9). The potassium data is from Table 1.2.

	Unit	Urine	Faeces	Total
Nitrogen	g/person per year	4000	550	4550
Phosphorus	g/person per year	365	183	548
Potassium	g/person per year			1200

Considering also the evidence of the value of urine and faeces in increasing food production (WHO, 2006, pp. 11-13), suggests that any tool that helps identify suitable technologies that can enhance the reuse of this fertiliser has value. An information processing architecture can assist in the task of exploring the potential inherent in the range of technologies that could enhance nutrient reuse.

As an example of this, consider that closure of the nutrient cycles would indicate a need to efficiently link the nutrient source with our food production systems. To this end, recycling of these nutrients will require transportation from the food consumption areas to the food production areas, the cost of

[1] For a cubical container the length of each side $L = \sqrt[3]{V}$ and surface area = $6L^2$.

which is primarily influenced by weight (the other component being distance of transport). Consequently, recycling of nutrients would be most cost effective with a high nutrient density. It follows that if carbon is removed from the organic matter then the nutrient density of the product will increase making the cost of transport proportionately less. Carbon removal occurs via microbial activity without needing human input if the moisture content is adequate. The rate of carbon removal by microbial activity is a time: temperature consideration and forms one of the constraints within which the technology needs to operate and is a question that is easily handled via a suitable Structure.

Nitrogen must also follow mass balance laws but is more complicated than for other nutrients as nitrogen can be lost as a gas. In terms of global warming there may be questions as to what form this gas is in or indeed, the preferred nutritional form for nitrogen (ammonium, nitrate, nitrite or gaseous forms); but these chemistry-type questions have links to the Structure. Consequently these considerations can be applied as a constraint to be reconciled by the designer of the technology.

Water requires particular consideration in the recycle/reuse question as on the one hand its presence is necessary if the carbon is being oxidised microbiologically, while on the other hand are the adverse consequences arising from transport costs, such as the higher water content of urine as compared to faeces. All of these have linkages to parameters within a Structure (quantity, and microbial kinetics – bacteria do not function without water), consequently they can form a part of the optimisation consideration.

Recycle of nutrients would require a break in the faecal:oral route for pathogens. Consequently, any technology combination that claimed to close the nutrient cycles would need to demonstrate that this pathogen route is absent.

3.3 Zero Pathogens

Pathogens are almost entirely sourced from the faeces so there is a distributional component across the three waste streams which have linkages to a Structure via the quantities and state of each component. To this distributional element must be added the significance of the faecal:oral route for pathogen transfer as a source of disease in humans. Historically disease is a driver for the development of sanitation technologies and the institutional frameworks that surround the issue.

From the theoretical perspective being argued here, pathogens are best considered as having two aspects: their need for nourishment in order to survive (in this respect they are no different from any other microbe and therefore implicit in any Structure via the carbon-based rate constant), and the pathogenic consequences for humans of their activities. As the pathogenic consequences for humans are not an inherent component of a Structure it requires special consideration.

A technology that deals with pathogenic consequences needs to break the faecal:oral route, for which there are a suite of possible strategies ranging from physical separation (including control of the insect vector) to destruction of the pathogens (by time/temperature, filtration, chemical, UV etc). Of particular relevance for this discussion is that when using a Structure it is possible for the significance of pathogen reduction to enter deliberations in a new form. Considering that a dead pathogen is not a public health risk (although toxins may persist for a period of time after the microbe dies), then incorporating the pathogen die-off kinetic into a Structure means that the public health element could enter deliberations via the output from the Structure. In making this linkage, public health concerns can directly influence the *requirements* of an optimum technology design rather than be an external, measurement based, constraint to the design criteria. In particular, the analysis can be further sub-divided into each waste stream to accommodate the difference in pathogen levels in each stream.

To enable this, a relationship between the pathogen die-off kinetic and the carbon-based rate constant would be required. This would then link the public health elements to the chemistry conjunction. There are 5 mechanisms for pathogen die-off: substrate depletion, antibiotics produced by other organisms, competition, temperature and time. The first three of these mechanisms are a function of the microbes that are present and could therefore be expected to have a correlation to the carbon-based rate constant and thereby linked to the Structure. Competition in particular is likely to be enhanced by consideration of the electron acceptor, as pathogens in the human gut have evolved for a warm anaerobic environment and will find it difficult to compete in an aerobic environment at a sub-optimum temperature. This author is not aware of any research that has attempted to find a linkage between the pathogen die-off kinetic and the carbon-based rate constant; however they are both logarithmic so some relationship can be expected. If a linkage is proven, then an additional pathogen control strategy that takes into consideration the different carbon-based rate constants could be added to the basket of techniques for pathogen destruction, and these incorporated into a technology design.

In contrast, the time: temperature relationship for pathogen death rates is well understood. Particularly at the higher temperature ranges due to research on thermophilic composting (Feachem, Bradley, Garelick, & Mara, 1983). This data suggests that at 20 ^{0}C residence times greater than 1 year would be required for safe pathogen destruction. At these time frames, the mass balance would need to accommodate the loss of carbon (and moisture), but the container size for a single person's faeces for *one year* is less than 50 L. Physically holding faeces for this length of time does not require an expensive container, albeit other requirements (such as the insect vector) may add to the cost. Therefore a technology that uses residence time as a pathogen control strategy could be considered for the highly pathogenic faeces, but only if they are collected separately from the other streams. The possibility that faeces-only technologies, which can cheaply achieve the residence times for the natural die-off kinetic to achieve the necessary pathogen destruction, and the question as to whether this may be a preferred technology is contained within the starting assumptions of the Structure.

4 Approaching a Structure with a question - Linking the analysis pathways

Consider a simplified Information Processing Structure based on linking only mass balance laws and microbial kinetics. Additional simplifications used in this example are: a single substrate with a first-order microbial kinetic utilising a single electron acceptor[2]. The change in substrate concentration (S) over time (t) is explained by Equation 1:

Equation 1

$$S_t = S_0 e^{-kt}$$

For this example, this is more usefully rearranged for time (t) and t becomes the residence time necessary for treatment (t_r):

[2] This simplified example is actually a special case of the full complexity. Composting contains 3 substrates (as distinct from the single one in this example). Similarly, a single electron acceptor is implicit in a single rate constant. This would only apply if that electron acceptor maintained a constant concentration throughout the system and there were no local concentration gradients, such as those observed in biofilms or the larger particle sizes of composting.

Equation 2

$$t_r = -\ln\left(\frac{S_t}{S_0}\right)\Big/ k$$

Applying mass balance laws to a number of people (n) with a quantity per person (Q_p) the container size required to physically hold the material over this time period is:

Equation 3

$$V_{tot} = Q_p \times n \times t = Q_p \times n \times \left(-\ln\left(\frac{S_t}{S_0}\right)\Big/ k\right)$$

Of particular note in Equation 3 is that a change in any of the parameters in the equation i.e. quantity per person, number of people, substrate type (implicit in only a single S_0), input concentration (S_0), exit concentration (S_t) and microbial kinetics (k) have a deterministic effect on the container size. For a continuously used system, the container size will increase with time unless one of two possible considerations are incorporated into the technology: either the necessity to have some overflow if container size is limited (such as a sewerage treatment system), or use a large container for which time (t_r) determines the amount of use before requiring emptying (compost toilet).

This very simplified Information Processing Structure therefore links environmental discharges (exit concentration S_t and quantity) with the beginning substrate (for which the particular component of the waste stream influences S_0 and Q_p), the level of use (n), the local climate (as it affects the microbial rate constant k) and elements of technology design (through-flow or occasional emptying); with a weaker linkage to the economic system (via the positive correlation between container size and cost – see Chapman (2015a) for details of these linkages).

Additional complexity can be built into the simplified Structure of Equation 3, such as including diffusion laws to explain the distribution of electron acceptors in composting, and locating Henry's law at the particle surface to explain how oxygen gets from the air into the particle (Chapman, 2008) etc. Adding complexity to the detail does not change the manner in which the Structure works, albeit there is a point where the model precision begins to reduce due to the problems of over-parameterisation – the concept of a Medawar zone is very useful in this respect (Grimm, et al., 2005).

Indeed, mass balance laws also enable separation of the system into different technologies whether in series or parallel, for example in Figure 1 mass balance laws enable determination of the concentration of B as being B = (A – Sediment). Similarly if B is a biological process then C = (B_{input} – degradation in B):

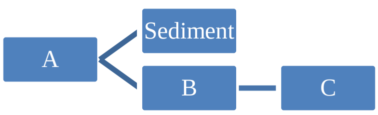

Figure 1 – Using mass balance to separately analyse components of a system that may be linked in series or parallel.

In Figure 1 the information processing architecture's physical boundary can be drawn such that it includes A, B, C and the sediment. In addition, while Figure 1 is drawn for sedimentation technology it can also apply to MBR technologies where only water is removed. In this case, the concentration of

B would increase, but this would have an effect on the Structure output (Equation 3) via a different value for S_0.

Other analysis systems can be applied to the basic Structure, for example thermodynamics could be used to determine a compost pile's inner temperature using a pile's thermal conductivity and the heat generated from composting. Similarly, a pile's response to diurnal temperature changes is a function of heat flows to and from the environment with thermal storage considerations in the compost and the technology surrounding the compost. For which thermal storage could be subdivided into water, VS, and ash if necessary, as all these components are implicit in the Structure.

4.1 Application to the faecal waste stream

Consider the faecal waste stream as an example of approaching a Structure with a question. This semi-solid has physical characteristics (frequency, volume and shape) and chemical characteristics, such as the proportion of each of 3 fractions identified in Chapman (2008). This experimental data applies to pig faeces but can be reasonably assumed to apply to human faeces. The pathogens are a third characteristic of the stream that requires addressing.

The question is "which technology will close the great cycles of Nature with no environmental effects"? While much is implicit in *no environmental effects* (zero water use, recycle of all nutrients etc), a further constraint for this question arises from the sustainability purpose requiring these to be done with zero energy and zero pathogen risk.

Given a semi-solid of a certain size and set of chemical characteristics then it is only necessary to have microbes for microbial degradation to occur. If this semi-solid is surrounded by air, then oxygen from the air can be reasonably assumed to diffuse into the surface of this semi-solid and be utilised by the microbes, consequently Equation 3 applies. A full set of equations modelling this process were derived by Chapman (2008) & (2009) and gave a very good regression with data ($r^2 > 0.99$ (Chapman, 2009)). However, a similar sequence of logic applies if this semi-solid is surrounded by water where the oxygen is supplied by the water rather than air – if oxygen is not present then other electron acceptors will be utilised. Build all the complexity into the model and the set of equations will describe the performance of **any** technology which is configured for the particular characteristics in the model's starting assumptions (composting in the case of Chapman (2008)).

This is still some way from identifying a 'particular' technology as a number of social (particularly pathogen control), technological and commercial constraints are required to further narrow the focus before the *requirements* needing to be met by a particular technology becomes apparent.

A Structure is composed of representations of all of the underlying laws and processes; it is in effect a virtual technology. All possible combinations for a technology that utilises the form that is implicit in the formulation of the Structure (such as composting) are included in the Structure output. We can therefore apply a combination of constraints to a Structure and use the output to articulate a set of requirements.

For example, consider the greatly increased options when the optimising parameter that is argued for composting (aerobic proportion (Φ) (Chapman, 2011)), is used to determine a set of requirements for a technology. Being an emergent parameter from a Structure, Φ_{pile} is affected by all those underlying parameters that are explicit in its derivation. Macro-scale parameters such as: level of use, aeration, container design, composting time etc., as well as micro-scale parameters: energy density of the pile, particle size, micro-porosity of the particles (as it affects the diffusion coefficient), temperature etc. will all affect the value of Φ_{pile}. It follows that if a value of Φ_{pile} better than some 'trigger value' is deemed to be an 'acceptable' technology then any combination of parameters that achieves this is also an acceptable technology. But this technology will be limited by the assumptions that the analysis is based upon.

To explain further the importance of the analysis assumptions, consider that a particle will have a low Φ when it is fresh as all the oxygen is consumed in the surface layer, however over time the outer layers become exhausted and oxygen penetrates further into the particle, resulting in an increasing Φ. It follows that a mix of old and fresh particles is a possible design strategy that arises in addition to the more direct linkages arising from particle size, temperature etc. However, each design strategy will have limits to its use (if more people use the technology in any particular day then the proportion of 'fresh' particles will increase, driving the value of Φ_{pile} down – level of use becomes an important design constraint), and each design will have a particular mix of manufacturing costs etc. This leads naturally to the notion of commercial niches.

While other socially imposed criteria may form part of the mix of requirements, a threshold value for Φ_{pile} is largely sufficient for the microbiological performance of the design to be assessed.

In addition, if pathogenicity is linked to the carbon-based rate constant (argued above) then pathogens can also form a component of this mix leading to a set of requirements. The time: temperature die-off kinetic for example can determine minimum holding times.

The path that the carbon and nutrients in the faecal waste take to complete the great cycles of Nature can be identified. These linkages between the fundamental laws and processes, microbial kinetics and the particular technology that we develop means that, while within the bounds of human influence, these paths determine the environmental impacts of the particular technology. We can choose a preferred path from a large number of possible paths.

A question can be formulated for each of the waste streams enabling identification of each waste stream's particular *requirements* needing to be met by the best technology. Social and commercial processes can then act on this information.

5 Discussion

The question of the separate treatment of each waste stream versus combining all three in effect requires a two-level optimisation procedure. As treatment of each waste stream can be optimised, then we must avoid any distortion that arises from comparing an optimised design with one which has not been optimised. Attempting this judgement by using only incumbent technologies (and the cost of these) bases the comparison on any structural biases that may have become embedded in the incumbent technologies. In particular, the research effort devoted to sewerage systems over the years is vastly greater than that devoted to technologies that treat only faeces, which indicates that using incumbent technologies for the comparison is at least questionable. Removal of these biases is possible using a Structure as the comparison can be based entirely on mass balance laws and microbial kinetics. These are independent of incumbent technologies.

That the case for the separate collection and treatment of faeces arises from **all** of the perspectives argued above (water use, recycle and pathogen control), makes the arguments for a *faeces* technology compelling. In addition, maximising nutrient recycle potential points to separate collection of urine as a preferred strategy and, as this can be an integral part of the faeces technology, then the case for separation of toilet wastes from greywater is further enhanced. The case argued above arises without consideration of energy use (Couper, July 2013), an analysis of which is highly likely to favour a dedicated toilet waste technology over a water flush system. Indeed, a complete system analysis would also include the treatment and supply of the potable water necessary for the flush.

The case for separate treatment of each waste stream therefore is very strong. The fact that such technologies struggle to make headway against the centralised, all mixed together, high water use sewerage system, indicates the need for a methodology that enables a fair comparison of separate treatment versus combined. Social processes that are based on unbiased information retain the potential for the best possible long-term solution, even if this potential is not grasped at the time of the decision.

Putting a series of constraints to a Structure is comparable to a highly directed sequence of trials with a virtual technology. Each constraint narrowing the focus to the most relevant part of the full complexity that, if built into a technology, would be workable as it would not violate any of the underlying fundamental laws and processes. Separating the virtual technology (the mathematical version of the underlying fundamental laws and processes) from the social processes that make decisions also locates the decisions in the same location in the complexity in which technologies develop. This is a useful synergy for enhancing the quality of our technological decisions.

6 Conclusion

Sustainability in dealing with our three waste streams points very strongly to the separate treatment of each waste stream. The use of an Information Processing Architecture to facilitate this process identifies yet another creative boundary between the technologies that meet the sustainability zeros and the commercial interface.

Framing the requirements around emergent parameters from a Structure has consequences:

- Bettering a single value in an optimising parameter points to a large number of possible responses to achieving the target value.
- In indentifying the value, all the conditions that led to that value then become the operating requirements for the particular technology.

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