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CENTER FOR RESEARCH AND ADVANCED STUDIES OF THE NATIONAL POLYTECHNIC INSTITUTE

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"On the Transforming Structure of Technology: Actions, Compositions and Associations"

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DISSERTATION

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Resumen

En el presente trabajo desarrollamos una teoría de la tecnología centrada en su estructura transformadora. Las bases de nuestro enfoque son a) la premisa de que la tecnología puede interpretarse en términos de acciones y b) la hipótesis de que estas acciones interactúan únicamente en dos formas: composición y asociación. Elaboramos una interpretación matemática de estos conceptos, así como también un método gráfico para operacionalizarlos. En el plano teórico, establecemos la conjetura de que toda tecnología, independientemente de su naturaleza, puede factorizarse en no más de quince diagramas elementales. Aplicamos nuestra teoría a tres sistemas tecnológicos: el taladro de arco, el taladro de bomba y la celda solar de silicio. También analizamos el caso de la fotosíntesis bajo este enfoque. Nuestros resultados muestran el potencial descriptivo y comparativo de la presente propuesta, así como también su utilidad para abordar el fenómeno de evolución combinatoria desde el punto de vista funcional.

Abstract

In this work, we develop an entirely transformation-based theory of technology. The bases of our approach are a) technology can be thought of as been made of actions and b) the hypothesis that actions interact in only two possible ways: composition and association. We develop a mathematical frame for these notions as well as a graphical approach to operationalizing these concepts. In the theoretical plane, we establish the conjecture that every technology, despite its nature, can be factorized into no more than fifteen elementary diagrams. We apply our theory to the analysis of three technologies the bow drill, the pump drill and the silicon solar cell. Photosynthesis is analyzed under this approach too. Our results show the usefulness of our approach in describing and comparing technologies. But also, they show the potential of our proposal to deal with the phenomenon of combinatorial evolution from a functional point of view.

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Chapter 1

Introduction

The study of technology has long relied on the research outlook of economics, sociology and philosophy. In turn, each of these disciplines are distinguished by the epistemological bases from which they choose to explore the world. As consequence, asking for a notion of technology face us with the theoretical multiplicity, inter- and intra-disciplinary, arising from these differences. Quoting Metcalfe (2010, p. 154)

> ... any particular answer usually depends on the wider framework of problems in which a concept of technology has to fit.

Yet, it is possible to find some common items that survive to epistemological change and remain intelligible under different approaches. Of special interest for us is what we call "the transforming structure of technology". Which, we argue, is twofold: the first one is, as pointed out by Sahal (1981), what the technology does, which defines its technical functions; the second, we propose, is what makes the technology do something, a sequence of structured transformations from which technical functions arise.

Perhaps, the notion of production function from Neoclassical Economics (Rasmussen, 2013; Debreu, 1954), is the earliest transformation-based conceptualization of technology. Roughly defined, it consists of a non-negative real-valued function f, for which $f(x) = y$ denotes the maximum output quantity y produced by the input quantity x. Whereof, $f(x) = y$ can be read as *x produces y* (Rasmussen, 2013, chap. 2). The scope of this notion is obvious, it is limited to represent production technologies and this view has remained unchanged along time (Metcalfe, 2010, p. 155). Out of the focus on production theory, the concept of technical function has been incorporated by some proposals coming from heterodox economics (Sahal, 1981; Saviotti and Metcalfe, 1984; Frenken and Nuvolari, 2004; Frenken, 2006). But even in this area, functions has been equated to numerical parameters subject to agents selection and no other role than their ascription to artifacts is assigned to them. This "functions as parameters" view extends to technological forecasting too (see for example Koh and Magee, 2006). Going beyond the previous perspective, the work of Arthur and Polak (2006) introduced a series of computerized experiments where the goal oriented nature of technical functions was explicitly operationalized. These experiments were addressed to the modeling of evolution by combinatorial innovation of technology, i.e. the creation of new technologies from combining the existent ones (Wagner and Rosen, 2014), through logical circuits and their logical functions serving as models for the "component" and "functional" halves of technology. Implicit in this work is the duality between what a technology does and how it works to achieve that goal. Thus, the combination of existent functions to produce new ones.

Technical functions also has been subject to philosophical examination (Kroes and Meijers, 2006; Hansson, 2006; Vermaas et al., 2013; Vermaas and Houkes, 2003). However, their transformative role, if invoked, becomes displaced soon by another concerns strongly related with human agency, or by essentialist discussions about their ultimate distinguishing elements. Between these inquiries it is worth to mention the work of Vermaas (2012), where technical functions are formalized as transformations between flows of energy, materials and signals. Formalization follows a like mathematical functions approach, however it is more symbolic than properly defined. It includes a parallel to functions composition having a distinct meaning than its mathematical counterpart. Finally, the work of Vermass was devoted to analyze functions-subfunctions decomposition through "composition" and no other relation between technical functions was explored.

Sociology is not indifferent to the subject that we are discussing about (see for example Dafoe, 2015). But, in comparison with philosophy and economics, it is absurd to expect any examination with no motivation mainly related to social shaping and the like. Therefore, what sociology has to say about the transforming structure of technology is out from the scope of this work. Summarizing, with exception of some isolated results, the transforming structure of technology has remained largely unexplored by the research outlook of economics, sociology and philosophy. Consequently, the existence of an organized framework to analyze this fundamental aspect of technology is still nonexistent or unknown. Therefore the motivation of this work, where the underlying reasoning is that the very notion of technology has epistemological value regardless its social, economical or philosophical "content". We find the study of its transforming structure to be a promising enterprise in the direction of this reasoning.

The present dissertation introduces an entirely transformation based framework to analyze the transforming structure of technology. For that purpose, we use the more general notion of action: to transform something is necessary to act on it. A technology then acts on something, but it is also composed of parts where each part acts on others. Consequently, our approach rests on the premise that technology can be thought of as made of actions, but we also advance the hypothesis that actions interact in only two ways: composition and association. In a formal setting, we present the mathematical expression of action, composition, association, and one axiom defining the way in which compositions and associations interact. We also introduce a graphical approach to operationalize these concepts. In the theoretical plane, we establish the conjecture that every technology, despite its nature, can be factorized into no more than fourteen elementary diagrams. Which is equivalent to state that, the way in which technology transforms the world (its technical functions) always can be equated to the way in which technology transforms itself to transform the world (the series of structured transformations from which technical functions arises). We apply our theory to the analysis of three technologies, the bow drill, the pump drill and the silicon solar cell. In addition, the process of photosynthesis is analyzed as an extension of our proposal to biological transformations systems.

Chapter 2

Fundamental Concepts

This chapter introduces the three key concepts of our approach: actions, compositions and associations. One additional item, the auto-completion axiom, defining the way in which compositions and associations interact is introduced too.

Actions

Actions, we claimed above, ultimately translate into transformations. These transformations are well defined in a proper space of representation. This motivates the next definition.

Let r denote an action, we define the mapping $r : X \to Y$, for given spaces of representation X and Y, to be the XY-representation of r.

Compositions

In a broad sense, compositions between r actions have the usual mathematical meaning of maps composition. However, we will distinguish two kinds of compositions:

Let $r : X \to Y$ and $s : Y \to Z$ be two actions, the composition $s \circ r : X \to Z$ is defined by $s(r(x)) = z$. In this first kind of composition, what is transformed by r is then transformed by s.

Consider now two actions $r : X \to Y$ and $s : Z \to W$, with $Y \neq Z$. The composition $(s, r) : X \to W$ will be defined as follows. Let $Y \cup^* Z \cup^* W$ with $\iota_0 : Y \to Y \cup^* Z \cup^* W$, $\iota_1 : Z \to Y \cup^* Z \cup^* W$ and $\iota_2 : W \to Y \cup^* Z \cup^* W$ to be the disjoint union of Y, Z and W. We define an equivalence relation $\equiv$ on $Y \cup^* Z \cup^* W$

as follows. For each $y \in r(X)$ we can choose a unique $z \in Z$ and $w = s(z)$, for such z and w we define $\iota_0(y) \equiv \iota_1(z)$ and $\iota_0(y) \equiv \iota_2(w)$. Then, $(s, r) : X \to W$ will be defined by $(s \circ \iota_1^{-1})(\iota_1(z) \equiv \iota_0(r(x))) = w$. By abuse of notation, we also will write $Y \equiv Z$. Here, the equivalences $\iota_0(y) \equiv \iota_1(z) \equiv \iota_2(w)$ imply $(s, r) \equiv e \circ r$, $e : Y \to Y$. That is, in this second kind of composition, what is transformed by r is not affected by s.

Actions composition $s \circ r$ (resp. (s, r)) defines a natural succession

$$X \xrightarrow{r} Y \xrightarrow{s} Z \; (\textit{resp. } X \xrightarrow{r} Y \equiv Z \xrightarrow{s} W)$$

which can be interpreted as *do r and then s.*

By definition, the composition of two actions is an action. Every abstract composition, regardless of its form $s \circ r$ or (s, r), will be portrayed as the directed edge $\overset{r}{\bullet}\!\longrightarrow\!\overset{s}{\bullet}$; each node being an action. Such edge will be called *composition edge.*

Associations

Abstract notion of association imitates the effect of an object acting on another to produce a desired effect, but this phenomenon seen in terms of actions. We next formalize such a notion.

Let $r : X \to Y$ and $s : Z \to W$ be two actions, an association from r to s is a mapping $f(r) = s$ endowed with an ordering $r \prec s$ such that $f(r) = s \iff r \prec s$. We call $f(r) = s$ to be an association mapping and we read the ordering $r \prec s$ as, r induces s.

We also will write $s \succ r$ as equivalent to $r \prec s$, i.e. $f^{-1}(s) = r \iff s \succ r$ with $s \succ r$ being read as, *s is associated to r*. The case $r \prec s$ and $s \prec r$ will be written as $r \sim s$.

By definition, the composition of two association mappings will be an association mapping. Every association mapping $f(r) = s$ will be portrayed as the directed dashed edge $\overset{r}{\bullet}\text{- - - -}\overset{s}{\bullet}$; each node being an action and the association map label being omitted. Such edge will be called *association edge.*

Auto-Completion Axiom

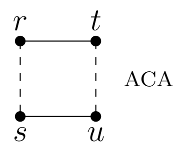
At this point, we have defined the three key concepts of our theory: actions, compositions and associations -the only two ways actions interact. We now define the way in which association and composition interact.

Axiom 2.1 *(Auto-completion Axiom, ACA). For any association mapping $f(r) = s$ and composition $t \circ r$ (resp. (t, r)), there is an action $u = f(t)$ such that $f(t \circ r) = u \circ s$ (resp. $f(t, r) = (u \circ s)$, $f(t, r) = (u, s)$).*

We have written $f(t, r)$ instead of $f((t, r))$ to simplify notation.

ACA tell us that if r induces s, then $t \circ r$ (resp. (t, r)) must extend the $\prec$ ordering to t for some u, $t \prec u$, with $u \circ s$ or (u, s). In extending $\prec$, the f association map is extended as $f(t \circ r) = f(t) \circ f(r) = u \circ s$ or just any other possibility including (t, r) and (u, s).

Using our graphical convention, the ACA axiom read as the square



Chapter 3

A Graphical Approach

Since we regard isolated actions as trivial cases, we take composition and association of actions to be our *elementary units*. For each one of these units we have developed a graphical notation: composition and association edges. We now introduce an operation between edges to show how more complex diagrams can be built by combining these elementary units.

Let e_i and e_j be either composition or association edges, a more complex diagram d_k, can be built by identifying nodes with the same label. Since we regard e_i and e_j to be elementary diagrams, $e_i = d_i$ and $e_j = d_j$, we will denote such *paste operation* as $(d_i, d_j) = (d_j, d_i) = d_k$. In the general case, we define (d_i, d_j) to be based on identifying n-nodes of the m-nodes contained in both d_i and d_j. We will define $d_k = (d_i, d_j)$ to be a *prime diagram* if both d_i an d_j are simple composition or association edges. Prime diagrams can be classified according to their shape. Thus, a shape-based equivalence relation can be defined to sort every possible prime diagram, each shape being an equivalence class. There are fifteen equivalence classes as shown in Table 3.1. When one node is shared we found bi-dimensional compositions (resp. associations) like shapes 1 and 3 (resp. 6 and 8). Another possible shapes are linear successions of compositions or associations like shapes 2 and 7. If both nodes are shared, equivalence classes include composition and association edges, shapes 4 an 9. But also, composition and association cycles, shapes 5 and 10. Where the curved down edge corresponds to the composition (resp. association) $s \circ r$ (resp. $r \prec s$), and the curved up one to the composition (resp. association) $r \circ s$ (resp. $s \prec r$). Shapes 11 to 15 are based on the combination between composition edges and association edges. With exception of shape 15, association edges are drawn with a vertical orientation in relation with composition ones. As the reader will note, class 11 corresponds to ACA. No auto-completion follows in 12 and 13 because asymmetry of association. Fifteenth diagram contains only one curved down edge preserving the meaning given above. Note also that the composition edge for $s \circ r$ is not curved and preserves the usual interpretation.

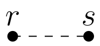
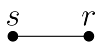
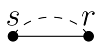
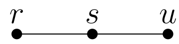
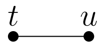
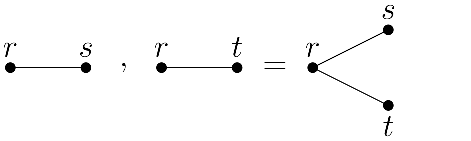
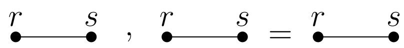
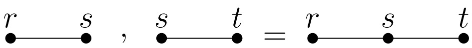
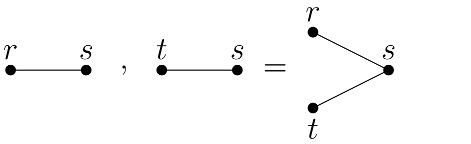
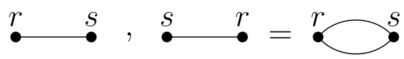
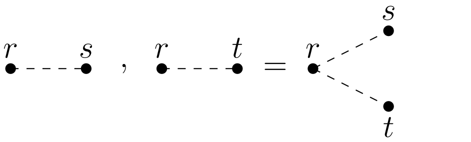
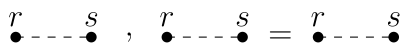
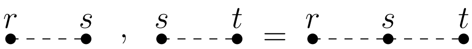
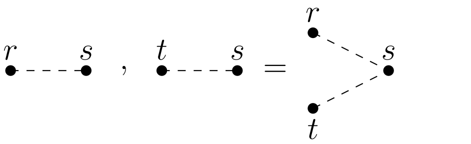
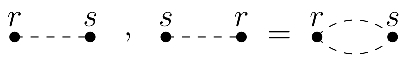
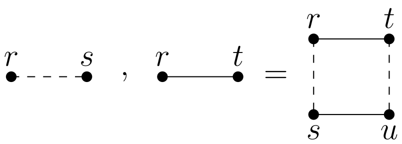
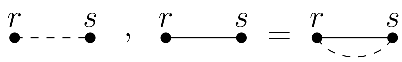
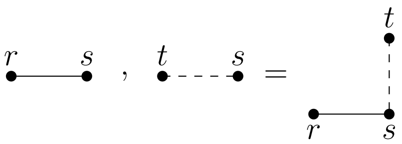
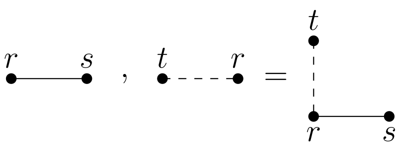
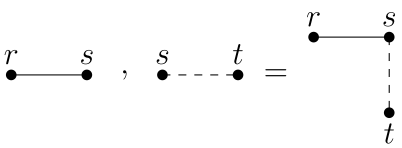
As an extension about curved edge notation, curved left-hand side (resp. right-hand side) edges will have the same interpretation than the curved down (resp. up) ones. This rule is designed for those cases where composition and association edges are set "orthogonal" as in 11, 12, 13 and 14. We define these fifteen diagrams to be the representative members of the equivalence classes conforming our shape-based equivalence relation. Every prime diagram is then equivalent to one of the fifteen shapes. This graphical approach extends the mathematical concepts provided in **Chapter 2**. It allows us to deal with multidimensional structures by operating a single entity. There is a sixteenth diagram which we will exclude from our analysis  ,  =  . When interpreted in terms of the order defined by $r \circ s$ (resp. (r, s)) and $f(r) = s$; we have *do s and then r*, and $r \prec s$. Thus, both interactions are mutually exclusive. In the context of transformations, the resulting diagram implies that a future action, r, induces a past one, s. For completion, let $(s \circ r) = t$ (resp $(s, r) = t$), we will say that  can be simplified as  when such simplification is convenient. We can proceed in a similar fashion with association maps to simplify associations edges.

Table 3.1: Set of equivalence classes for prime diagrams

One node shared	Two nodes shared
1 	4 
2 	
3 	5 
6 	9 
7 	
8 	10 
11 	15 
12 	
13 	
14 	

Chapter 4

Some Illustrative Examples

In this chapter we show how the concepts developed in **Chapter 2** and **Chapter 3** can be applied to technological analysis. Here an XY-representation of any r action will stand for a concrete transformation like slide the bow, rotate the spindle, etc., depending on the system we analyze. Note that, in general, the specific form of $r : X \to Y$ will not matter to us. However, keep in mind that the abstract representation of an action should reflect the limits and properties of the technological system where this action comes from. For the purposes of our approach it is sufficient for r to reflect restrictions on composition and reversibility.

Once that the abstract notion of r action is connected with technological transformations, we set the next rules to define auto-completion. Consider $f(r) = s$ and $f(t \circ r)$, then follow the next rules to set $f(t)$ by auto-completion:

R0) if $r = t$ and there is no restriction for composition, set $f(t) = s$.

R1) if $t \neq r$, $f(t)$ is defined according to our empirical knowledge about technology.

R2) if $r \neq t$ and nothing is suggested by the empirical knowledge, set $f(t) = e$, the identity or nil action.

We now establish a special rule for the case $s \circ s$ undefined:

R0′) if $r = t$ and there is restriction for composition, set $f(t) = e$.

4.1 Bow Drill

The bow drill is an ancient device composed of a bow tied to a spindle in whose top it is placed a cap, say, a stone cap (Gorelick and Gwinnett, 1981). As illustrated in Figure 4.1, when the bow slides to the left or right, the spindle rotates clockwise or anti-clockwise and pressing (small black triangle) the cap drives the spindle into the object. The pressure on the cap also transmits to the object. Bow drill invention dated to the Upper Paleolithic, when it was used to bore objects like vessels and beads (Gorelick and Gwinnett, 1981).

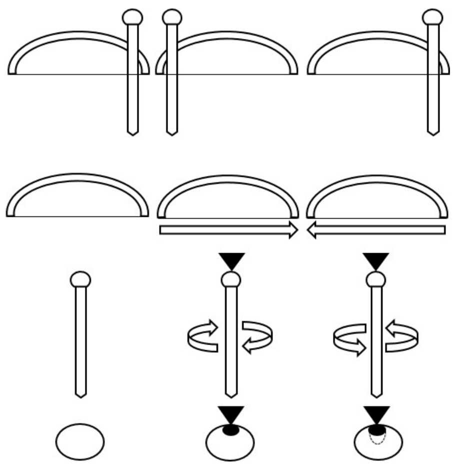
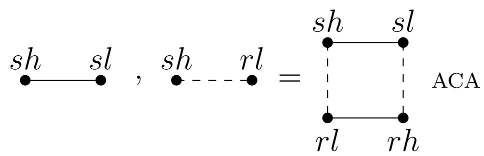
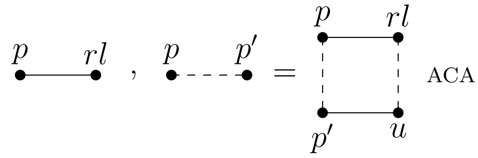


Figure 4.1: Bow Drill under two movements

Next, we will reconstruct Figure 4.1 by using our diagrams notation and the paste operation in the previous section. Our starting point will be

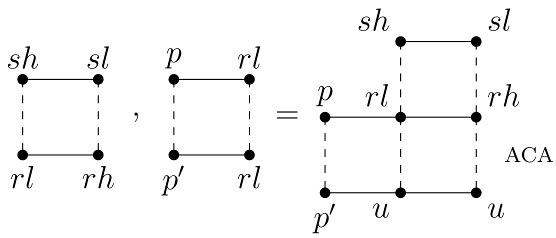


With this diagram we denote the whole sliding right sh and left sl of the bow, $sl \circ sh$, as a complete cycle $rh \circ rl$ of rotations for the spindle. The meaningful relations between these actions we want to highlight are: $sh = sl^{-1}$, $rh = rl^{-1}$, and $sh \circ sh$, $sl \circ sl$ being undefined. We continue with

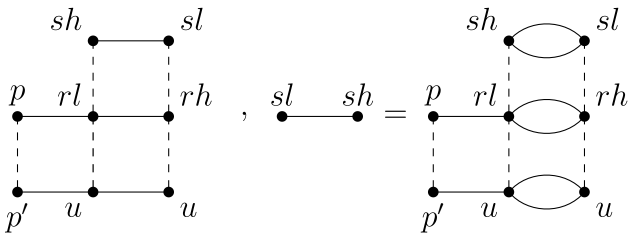


which expresses the composition of pressing p and rotating-left rl the spindle, (rl, p), as the (u, p') composition of pressing and drilling some object. Here, we see two of examples of the kind of compositions where what is done by p (resp. p') is independent of what is done by rl (resp. u). Since no object can be drilled indefinitely, denoting $u^2 = u \circ u$, $u^3 = u \circ u \circ u$, and so on, we will set u to be such that $u^k = u^n$, for every $k \geq n$ for some $n > 1$.

If we paste both prime diagrams we get



which will be encoded as $((u \circ u), p') = f_2(f_1(sl \circ sh), p)$, $f_1(sl \circ sh) = rl \circ rh$. We then paste together

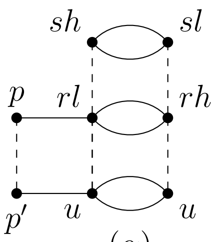


resulting in the composition cycles $sh \circ sl \circ sh$, $rl \circ rh \circ rl$ and $u \circ u \circ u$. These cycles can be iterated up to the n-th case, where $u^k = u^n$ for every $k \geq n$. That limit represents the case when the object gets drilled from side to side. Results from these iterations generalizes $((u \circ u), p') = f_2(f_1(sl \circ sh), p)$ to $(u^{2m}, p') =$

$f_2(f_1(sl \circ sh)^m, p)$ for $m \geq 1$.

Owing to $sh = sl^{-1}$ and $rl = rh^{-1}$, $f_1(sl \circ sh) = (rh \circ rl)$ becomes $f_1(e) = e$. That is, f_1 preserves the identity. But, $f_2(rh \circ rl) = (u \circ u)$ yields $f_2(e) = u^2$. Thus, f_2 does not preserve the identity through association. If we extend $f_2(e) = u^2$ to $f_2(rl \circ e) = u^3$, we get a contradiction since $f_2(rl) = u$ and $rl \circ e = rl$, that is $f_2(rl \circ e) = f_2(rl)$ does not follows. This issue is solved by establishing a condition to $f_2(rl)$ based on $(u^{2m}, p') = f_2(f_1(sl \circ sh)^m, p)$, where $f_2(rl) = u^{2m+1}$ when association comes by auto-completion of the form $f_2(rl \circ e)$ with $e = (rh \circ rl)^m$. Another required condition is that of $f_2(e) = u^{2m}$ for $e = (rh \circ rl)^m$, $m \geq 1$.

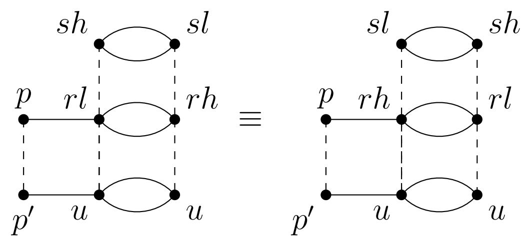
Returning to our compositions cycle depiction



(α)

(α) denoting the cycles $sh \circ sl \circ sh$, $rl \circ rh \circ rl$ and $u \circ u \circ u$ taken place $\alpha - times$. We have $f_2(rl) = u^{2m+1=\alpha}$ for the above rule.

To end our analysis, we stress the preservation of association given by $f_1(sh \circ sl) = f_1(sl \circ sh)$ and $f_2(rh \circ rl) = f_2(rl \circ rh)$ as

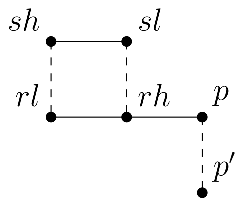


That is, the order of the sliding does not affect the final result. This empirical fact is consistent with the formal results

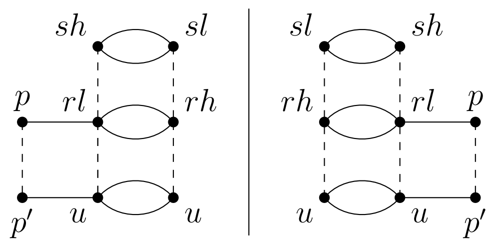
$$f_1(sl \circ sh) = f_1(sl) \circ f_1(sh) = e = f_1(sh) \circ f_1(sl) = f_1(sh \circ sl)$$

$$f_2(rh \circ rl) = f_2(rh) \circ f_2(rl) = u^2 = f_2(rl) \circ f_2(rh) = f_2(rl \circ rh)$$

However, as we know, if pressing does not precedes rotation, then no drilling is produced.



The absence of $rl \prec u$ and $rh \prec u$ in the above diagram is justified from the empirical point of view. The abstract explanation on the other hand suggest a different picture. What we know by ACA is that, let $f_2(p) = p'$ and $f_2(rl, p)$, there exists $f_2(rl) = u$ such that $f_2(rl, p) = (f_2(rl), f_2(p)) = (u, p')$. Hence, let $f_2(rl) = u$ and $f_2(p, rl)$, there exits $f_2(p) = p'$ such that $f_2(p, rl) = (f_2(p), f_2(rl)) = (p', u)$. Which, as we argued above, is inconsistent with the empirical facts. In the language of diagrams, this looks as the reflection



Where only the left-hand side depiction is empirically consistent.

4.2 Pump Drill

The pump drill is a device composed of a perforated crossbar tied to a spindle and a perforated flywheel below the crossbar (Zhao et al. (2017)) (see Figure 4.2). Starting from Figure 4.2 (left), when the crossbar slides down the spindle and the flywheel are rotated by the unwinding process of the threads tying the crossbar and the spindle. Once that the unwinding process has finished (middle), the rotating flywheel keeps spinning the spindle, starting a process of winding which yields the

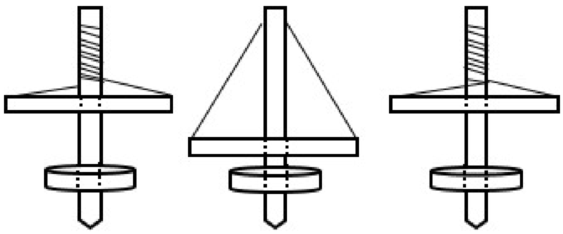
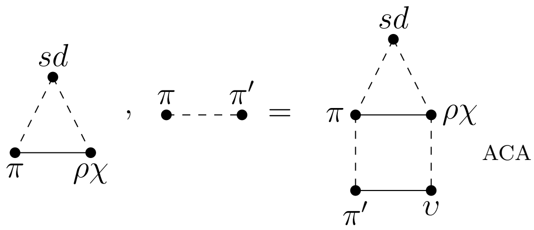


Figure 4.2: Pump Drill

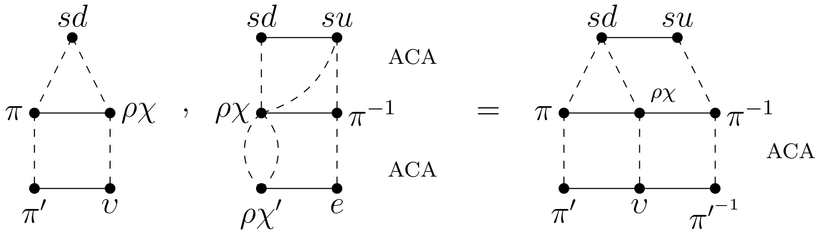
sliding up of the bar (right). If the crossbar is slided down again, it induces a rotating movement in the opposite direction (Zhao et al. (2017)).

We now proceed with the corresponding analysis. Our first diagram is

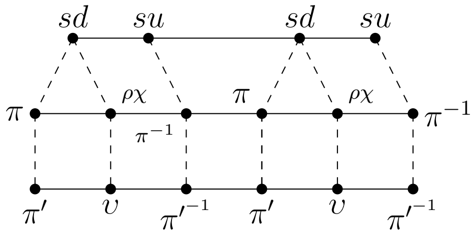


This diagram depicts a bi-dimensional association. On one hand, the sliding down of the crossbar induces pressing the spindle, which induces pressing the stone bead: $sd \prec \pi \prec \pi'$. On the other hand, the sliding down of the crossbar induces either clockwise or anticlockwise rotation of the spindle, which in turn induces drilling some object by ACA: $sd \prec \rho\chi \prec \upsilon$.

The second diagram comes by pasting together



Where the middle diagram gives account of the sequence: sliding the bar induces the rotation of the spindle which in turn rotates the flywheel, the continuing rotation of the flywheel rotates the spindle and (winding the threads) slides the bar up. That is, $sd \prec \rho\chi \prec \rho\chi' \prec \rho\chi \prec su$ with the association cycle $\rho\chi \sim \rho\chi'$. Here, the upward association mapping from $\rho\chi$ to su gives rise to the auto-completions $(su \circ sd) \prec (\pi^{-1}, \rho\chi)$, and consequently $(\pi^{-1}, \rho\chi) \prec ({\pi'}^{-1}, \upsilon)$ in the right-hand side diagram. Since stopping the pressure on the spindle does not affect the wheel, the remaining auto-completion is set $(\pi^{-1}, \rho\chi) \prec (e \circ \rho\chi')$. The resulting diagram portrays the crossbar cycle $su \circ sd = e$ and the entire process $(({\pi'}^{-1}, \upsilon), \pi') = g_2(h_1(su \circ sd), g_1(sd))$, $h_1(su \circ sd) = (\pi^{-1}, \rho\chi)$ and $g_1(sd) = \pi$. Note that, in order to facilitate visualization, the right-hand side diagram excludes $\rho\chi \succ su$, $\rho\chi \sim \rho\chi'$ and $(e, \rho\chi)$ edges from the middle diagram. Based on the information given by $\rho\chi \succ su$ we could extend the previous expression to $(({\pi'}^{-1}, \upsilon), \pi') = g_2(h_1(i_3(\rho\chi) \circ sd), g_1(sd))$, with $i_3(\rho\chi) = su = i_3(i_2(i_1(h_1(sd))))$, i.e. $sd \prec \rho\chi \prec \rho\chi' \prec \rho\chi \prec su$. If the cycle repeats again, we get



the corresponding equation being

$$(({\pi'}^{-1}, \upsilon), \pi', ({\pi'}^{-1}, \upsilon), \pi') = g_2(h_1(su \circ sd), g_1(sd), h_1(su \circ sd), g_1(sd)).$$

Generalizing, $(({\pi'}^{-1}, \upsilon), \pi')^n = g_2(h_1(su \circ sd), g_1(sd))^n$.

4.3 Silicon Solar Cell

A solar cell is a device for the direct conversion of light into electrical energy through the photovoltaic effect (Ashock et al., 2018). Classical and simpler structure of silicon (Si) solar cells consists of the front electrical contact, an antirefelctive coating, the n-type layer, the p-type layer, the p^+-type layer and the back electrical contact (Hersch and Zweibel, 1982; Miles et al., 2005). As shown in Figure 4.3, the boundary between the n-type layer and the p-type layer is called *p-n junction*.

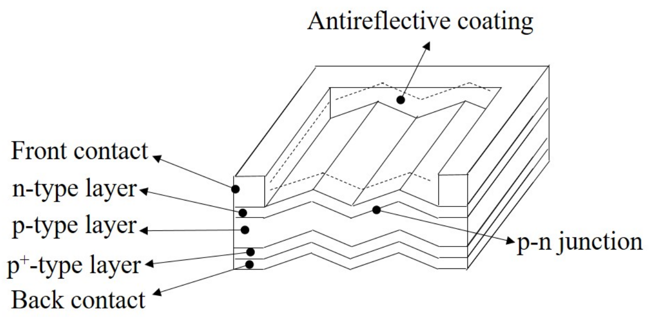


Figure 4.3: Classical structure of a Si solar cell

Since the n-type layer has a surplus of free electrons, whereas the p-type layer has a shortage of valence electrons to form bounds -each of these absent electrons being interpreted as a “hole”-. When the two layers meet, an electrical field is built around the p-n junction. This due to, the free electrons (from the n-type layer) and the holes (from the p-type layer) are attracted between them until reach equilibrium. The result is an area around the junction, termed as *depletion zone*, where the adjacent side of the n-type layer is positively charged and the adjacent side of the p-type layer is negatively charged (Hersch and Zweibel, 1982). Finally, the role of the p^+ type layer is that of lowering the back contact resistance and to create a field that repeal the free electrons on the p-type layer towards the junction (Miles et al., 2005).

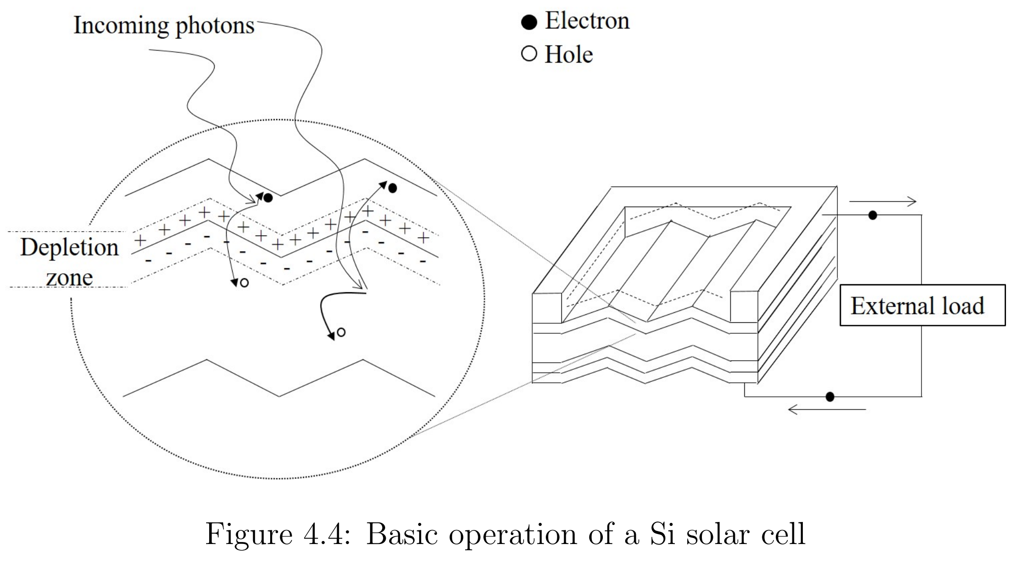
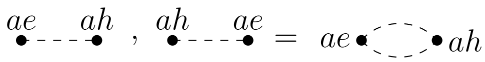


Figure 4.4: Basic operation of a Si solar cell

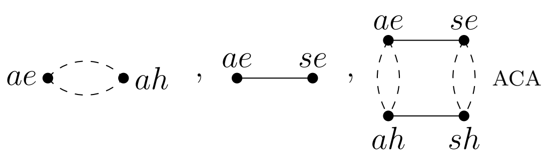
If a photon coming from a light source, say sunlight, excites some electron from either the n-type layer or the p-type layer, and such photon has the right energy, the electron releases from its bound and it is free to move around the layer. However, when such electron come close to the depletion zone, the electrical field repeals it to the n-type layer. In a similar fashion, the hole created by that electron is repelled to the p-type layer, regardless the layer where it was created. This produces a charge imbalance into the cell. If an external load is connected to the contacts of the cell, electrons being produced by the previous way are allowed to flow towards the p-layer through the circuit. That flow can be leveraged to do useful work like heating the filament of a light bulb (Hersch and Zweibel, 1982).

We next introduce the corresponding diagrams for this technology. The first are



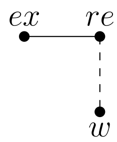
where adding free electrons to the n-type layer induces adding holes to the p-type layer, $ae \prec ah$. This represents photons absorption and charge separation. Since electrons and holes are created in pairs, electron-hole pairs, we also have $ah \prec ae$. That is, $ae \sim ah$.

The second part of our diagram comes by allowing electrons flow to recombine with holes. That is, subtracting electrons induces subtracting holes $se \succ sh$; but also, $se \succ sh$:



Once again, we adopt the logic to choose auto-completions in order to get the right description. In this case, the cycle $se \sim sh$ comes by auto-completion: $ae \prec ah$, $(se \circ ae) \prec (sh \circ ah)$, $ah \prec ae$ and $(sh \circ ah) \prec (se \circ ae)$. We extend cycle notation to $(se \circ ae) \sim (sh \circ ah)$. Until now we have drawn a diagram for how a Si solar cell transforms itself. To extend such diagram to how a solar cell transforms the world, i.e. other objects than itself, we proceed with a simplification.

First, we note that $ae = se^{-1}$ and $ah = sh^{-1}$. Furthermore, the association cycles $ae \sim ah$ and $ah \sim sh$ are not but two different ways to describe the same phenomena, electrons excitation and electron-hole recombination. In turn, these two phenomena constitutes the two ends of electrons flow trough a load connected to the cell. Based on these observations, we set $ex = ae \times ah$, $re = se \times sh$, $re \circ ex = (se \circ ae) \times (sh \circ ah)$. Where ex and re denote electrons excitation and electron-hole recombination respectively. This reduces our solar cell depiction, the load included, to:

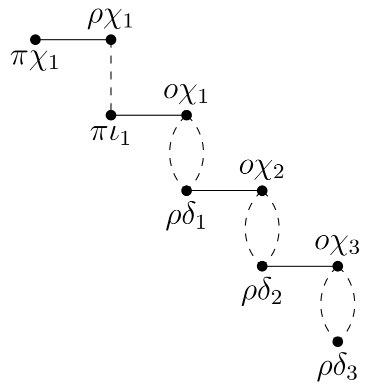


With $re \prec w$ representing the induced work to an external load given by electrons flow. The resulting diagram cannot be simplified to a single equation like in the previous cases. This time, we are given with $re \circ ex$ and $j(re) = w$, also written as $j^{-1}(w) \circ re$.

4.4 Beyond Technology: Photosynthesis

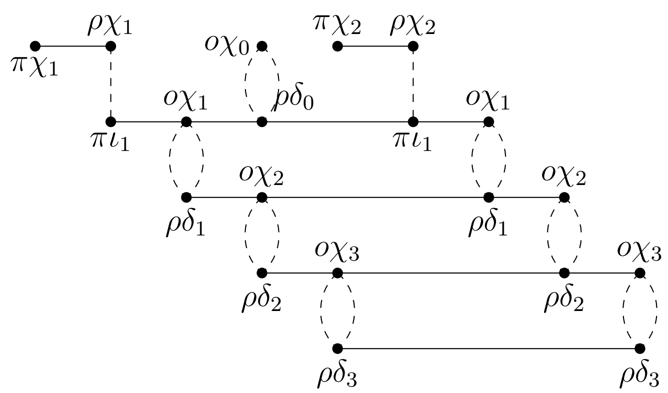
The photosynthesis use the energy from light to break water to obtain hydrogens and electrons and oxygen as secondary product. The photoreactions happen in the thylakoid membranes of the chloroplasts of plant cells. The thylakoids have proteins complex known as photosystem I and photosystem II (PSI and PSII), which work in conjunction to remove electrons and hydrogens from water and transfer by redox reactions electrons and hydrogens to the $NADP^+$ to form NADPH, necessary to carbohydrate synthesis. For the purposes of this example, we will focus our attention in the electrons transference from PSI to PSII; the so-called Z-scheme. Next, we provide a detailed description of this process.

In order to save space, the graphical depiction of this biological process will be introduced without making explicit the pasting operations between diagrams. However, the usual stepwise representation approach will be followed. Here is the first diagram



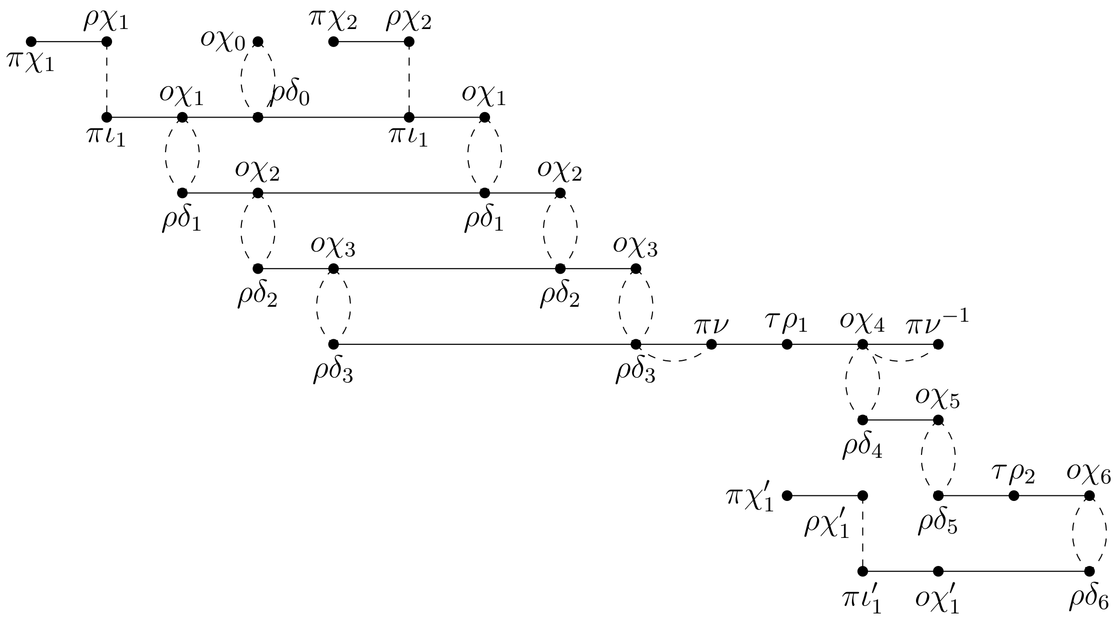
what is depicted above are: photoexcitation of an antenna molecule followed by relaxation of this antenna caused by electron decaying to its ground state ($\rho\chi_1 \circ \pi\chi_1$); photoionization of a P_{680} chlorophyll-a molecule induced by $\rho\chi_1$ ($\rho\chi_1 \prec \pi\iota_1$); Pheophytin (Pheo) reduction induced by P_{680} oxidation ($o\chi_1 \sim \rho\delta_1$), written as an association cycle because it depicts a redox reaction; Q_A plastoquinone reduction induced by $Pheo^-$ oxidation ($o\chi_2 \sim \rho\delta_2$); and Q_B plastoquinone reduction induced by Q_A^- oxidation ($o\chi_3 \sim \rho\delta_3$) (Govindjee et al., 2010; Tikhonov, 2014; Rojas et al., 2016). Where each each redox reaction involves one electron transference. These transformations take place into the PSII. Auto-completions $(o\chi_2 \circ \rho\delta_1) \prec (e \circ o\chi_1)$, $(e \circ o\chi_1) \prec (e \circ \rho\delta_1)$, $(o\chi_3 \circ \rho\delta_2) \prec (e \circ o\chi_2)$ and $(e \circ o\chi_2) \prec (e \circ \rho\delta_2)$ are not drawn. As a general rule, trivial auto-completions like these will be ignored in the subsequent diagrams.

In order to describe next steeps of photosynthesis, we require a second set of transformations given as follows



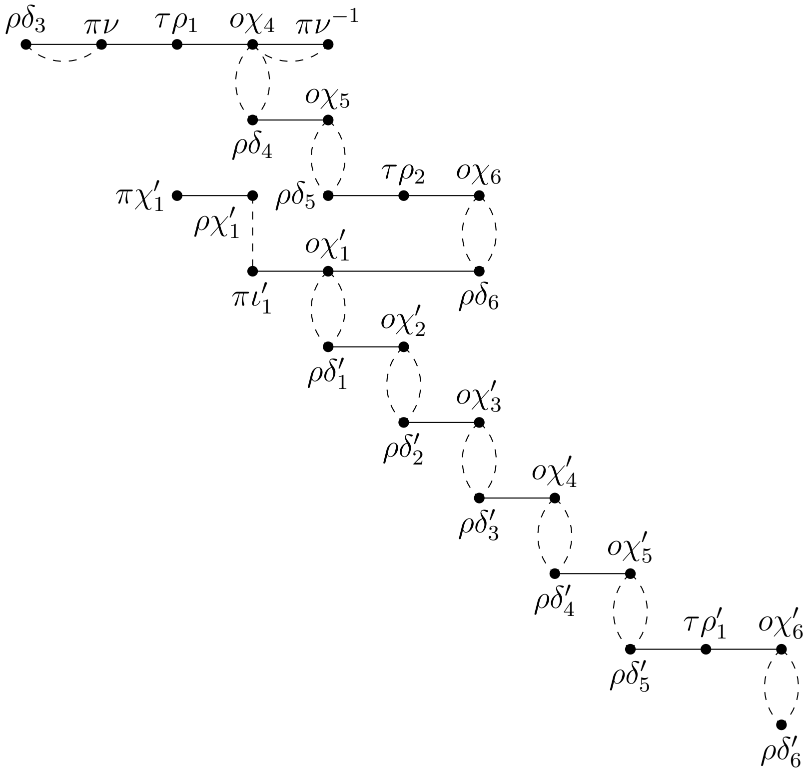
First, we have P_{680} reduction induced by the (partial -one electron-) oxidation of two water molecules ($o\chi_0 \sim \rho\delta_0$). Next transformations are a copy of the previous ones: the antenna relaxation induces P_{680} photoexcitation ($\pi\chi_2 \prec \pi\iota_1$), and the path of redox reactions described above is repeated. At the end of this process, Q_B gains two electrons, this is represented by the composition $\rho\delta_3 \circ \rho\delta_3$.

Transformations following $\rho\delta_3 \circ \rho\delta_3$ are



where $\rho\delta_3$ induces protonation of the reduced Q_B^{2-} plastoquinone given by the addition of two H^+ protons coming from the stroma ($\rho\delta_3 \prec \pi\nu$ with $\pi\nu \circ \rho\delta_3$). Next, protonated Q_B^{2-} (PQH_2) is translated towards its binding site in the cytochrome b_6f complex ($\tau\rho_1 \circ \pi\nu$) (Govindjee et al., 2010; Tikhonov, 2014). This is followed by b_6f reduction induced by PQH_2 oxidation ($o\chi_4 \sim \rho\delta_4$) and b_6f partial oxidation induced by plastocyanin PC oxidation ($o\chi_5 \sim \rho\delta_5$). This time, $o\chi_4 \sim \rho\delta_4$ involves a two electrons transference, whereas $o\chi_5 \sim \rho\delta_5$ only involves one electron (Tikhonov, 2014; Laisk et al., 2016). As PQH_2 is oxidized its two protons are released to the lumen; thus we have $\pi\nu^{-1} \circ o\chi_4$. After $o\chi_5 \sim \rho\delta_5$, PC is translated towards its binding site in the PSI system where it reduces a previously oxidized P_{700} molecule ($\tau\rho_2 \circ \rho\delta_5$ and $o\chi_6 \prec \rho\delta_6$). Finally, P_{700} is oxidized in the same way than P_{680}: $\rho\chi_1' \prec \pi\iota_1'$ with $o\chi_1' \circ \pi\iota_1'$.

For reasons of space, we introduce the fourth stage of our depiction without including the first succession of redox reactions.



This diagram includes the redox reactions between P_{700}^- and the A_0 chlorophyll-a molecule ($o\chi'_1 \sim \rho\delta'_1$); $A_0{}^-$ and the A_1 phylloquinone molecule ($o\chi'_2 \sim \rho\delta'_2$); A_1^- and the F_x iron-sulfur complex ($o\chi'_3 \sim \rho\delta'_3$); F_x^- and the F_{AB} iron-sulfur complexes ($o\chi'_4 \sim \rho\delta'_4$); as well as F_{AB}^- and the Fd ferredoxin iron sulfur protein ($o\chi'_5 \sim \rho\delta'_5$). It also includes the translation of Fd^- from PSI to the FNR enzyme, $\tau\rho'_1$, followed by the redox reactions between Fd^- and FNR ($o\chi'_6 \sim \rho\delta'_6$)(Makita and Hastings, 2016). Reduction of a second PC at the b_6f complex leads to FNR^{-2} reduction followed by $NADP^+$ reduction induced by FNR^{-2} oxidation. On the other hand, in PSII two water molecules are fully oxidized with the double reduction of a second PQ (Govindjee et al., 2010). These processes are not depicted here.

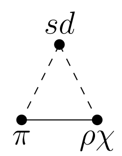
Synthesizing the above diagrams into a single equation results impossible because the multiple starting paths and end points at each depiction. The analysis of photosynthesis was introduced in order to show the use of our approach in structuring more complex transformations systems than the previous ones, in spite of their nature.

Chapter 5

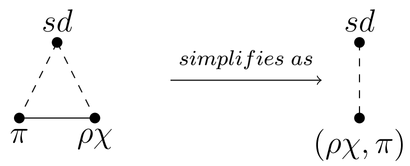
Theoretical Issues

Previous examples were mostly based on artifacts, however technology does not reduces to artifacts only. Hence, a critical question is about the extension of our approach to the entire realm of technology. The answer lies on the central premise of our approach: *technology can be thought of as been made of actions, and actions ultimately translate into transformations.* Following this line of reasoning, we ask us, is there any instance of technology where transformation is absent? Our argument is that, when we think about technology, even the human agency notion is dispensable, but its transforming structure does not. In what regards to the generality of our approach. The Si solar cell example shows how composition and association go beyond mechanical devices. Think, for example, on writing systems as technologies. In spite of their abstractness, in a very broad sense, these kind of technologies can be seen as the composition between two actions: encoding and decoding.

The second issue we raise to discussion is that of two actions operating simultaneously on some object. How do we classify such interaction? To give a concrete example, let us to return at the pump drill example from **Chapter 4**. For that technology we drew

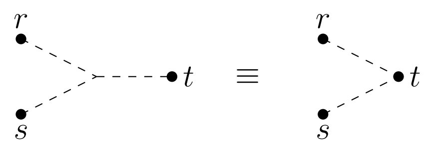


to denote, sliding down the bar (sd) induces pressing (π) and rotating ($\rho\chi$) the spindle. Our diagram introduced the composition $(\rho\chi, \pi)$, but actually these actions operate simultaneously on the spindle. Despite our proposal is to deal such interactions as compositions. We do not exclude the possibility to simplify

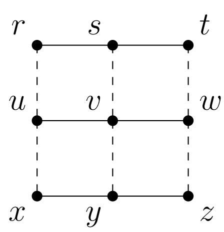


Thus, we still interpreting simultaneity as a composition, note we choose $(\rho\chi, \pi)$ instead of $(\pi, \rho\chi)$ to have the desired result (υ, π'), but we associate such composition to sd as a single action. Still, we think this theme requires more research.

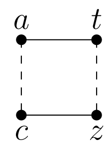
Regarding the concept of association, until now our work is based on "single-variable associations", i.e. $f(r) = s$. However, nothing prevent us to speculate about the possibility to observe "multi-variable associations", intuitively $\varphi(r, s, ...) = z$, φ being like the usual association map. Where r, s, etc. are all required to induce z. This is also a theme we think requires more research. But if we are faced to say something else on the subject. We propose to split $\varphi(r, s, ...) = z$ into single-valued association maps $f(r) = z$, $g(s) = z$, etc. For example, $\varphi(r, s) = t$ will lead to the equivalence



We end this section discussing the use of our approach to deal with "larger" technologies. Consider one hypothetical technology represented by



being encoded as $z \circ y \circ x = f_2(f_1(t \circ r \circ s))$, $f_1(t \circ s \circ r) = w \circ v \circ u$. Whereas there might be interest in studying in detail such structure, for other purposes a broader approach could be of more use



encoded as $z \circ c = h_1(t \circ a)$. Where $a = s \circ r$, $b = v \circ u$ (not shown above), $c = y \circ x$ and $h_1 = f_2 \circ f_1$. In the second case, actions a and c are defined without making reference to r, s, x and y, and the associating map h_1 is defined in terms of these two actions. We know that turning on a computer requires pressing a button, even if we ignore what happens "inside" once that we press that button. At the end, the result is independent of our knowledge (until it is not). We also have shown that another kind of simplifications are possible like in the case of the solar cell.

How finer a technological description could be will depend on the limit where actions interactions reduce to physical or chemical phenomena for which standard scientific descriptions are more suitable.

Chapter 6

Concluding remarks

We have introduced a framework to explore the transforming structure of technology. Our examples show that sometimes we can encode this structure into a single equation. But other times, these transforming structures cannot be further simplified. This will depend of the technology we are analyzing about. On the opposite side, our approach allows technological comparison between technologies of the same or different class. Diagrams are useful to provide a visual way to contrast transforming structures. For example:

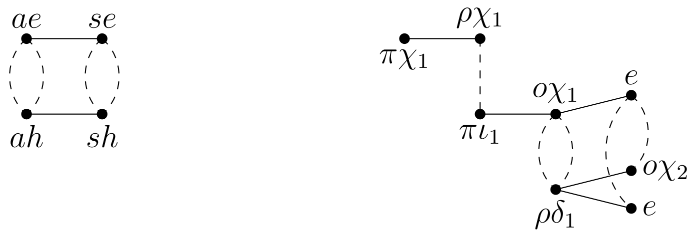
allow us to compare two related technologies, the bow drill (left-hand side) and the pump-drill (right-hand side) in terms of how a similar set of actions are organized in a different way to achieve the same goal. That comparison is also possible for their respective equations

$$(u^{2m}, p') = f_2(f_1(sl \circ sh)^m, p)$$

$$((\pi'^{-1}, \upsilon), \pi')^n = g_2(h_1(su \circ sd), g_1(sd))^n$$

In the both cases we can observe the extra association mapping of the pump drill structure in comparison with the bow drill one. Moreover, extending the analysis up to the ultimate interaction will show us the hidden association maps from *sd* to *su*.

Comparison extends to other instances than technology. That is the case of the Si solar cell and the photosynthesis process:



Wherein the cycle $(se \circ ae) \sim (sh \circ se)$ is not followed for the similar kind of transformations taking place in photosynthesis. It is true however that, to draw each diagram we have to know technology or the system we are analyzing. Therefore, a future line of research is the introduction of more advanced analytical tools to bring new knowledge about technology or related systems based on our approach.

Going away from technical discussions, we stress the connection of our work with the *intentional sense* of technology. Quoting what is perhaps the most enlightening statement of philosophy of technology, that

> ...in a twofold sense, human beings produce technical artefacts: in a physical and in an intentional sense (Kroes and Meijers, 2006, p. 1).

We find that, technical functions precedes even the physical sense. Indeed, earliest stone technologies had to came from nothing than the intention to transform something by using the available resources in nature. Thus, if we accept the intentional condition of technology, as well as combinatorial evolution to be the major mechanism underlying technological change. Then, we have to recognize the weight of actions combination in the process of technological evolution. But, as was laid down in the introduction, the study of this phenomenon seems to be of little interest for science and philosophy. Yet, the present work provides a framework to analyze technology and technological change under the light of actions combination by composition and association.

To end this work, we establish the conjecture that *every diagram not being a composition nor an association diagram, can be factorized into no more than the fifteen prime diagrams.* In the statement, two prime diagrams are regarded as different if they pertain to different equivalence classes. First, note that every d_i diagram has a trivial factorization of the form $d_i = (d_i, d_i)$; and for the case of composition and association diagrams this is the only possible factorization. For any other diagram there is at least one non-trivial factorization $d_k = (d_i, d_j)$ with $d_i \neq d_k \neq d_j$. Hereinafter we will deal with non-trivial factorizations. Let $d_k = (d_i, d_j)$ to be a diagram, then either d_i and d_j are prime diagrams, which end the factorization, or at least one of them is not. In the second case, we can state $d_i = (d_l, d_m)$ and $d_j = (d_n, d_o)$ for some d_l, d_m, d_n and d_o diagrams. In this way $d_k = (d_i, d_j) = ((d_l, d_m), (d_n, d_o))$. We can repeat the process for d_l, d_m, d_n and d_o, and so on, up to the *nth*-step where, every $d_z = (d_x, d_y)$ diagram to the right-hand side of the equality is a prime diagram. Since we have constructed the set of shape-based equivalence classes, it must to follows that all the resulting diagrams are contained into some of the fifteen equivalence classes. If the argument holds true, every technology would be the combination of only fifteen basic, prime, technologies. Provided that our hypothesis about actions interactions is true.

Bibliography

Arthur, W. B. and Polak, W. (2006). The evolution of technology within a simple computer model. *Complexity*, 11(5):23–31.

Ashock, S., Fonash, S. J., Fonash, R. T., Hosch, W. L., Rogers, K., Sampaolo, M., Singh, S., and Tikkanen, A. (2018). *Solar Cell*. Encyclopædia Britannica. Retrieved August 19, 2019, from `https://www.britannica.com/technology/solar-cell`.

Dafoe, A. (2015). On technological determinism: A typology, scope, conditions, and mechanism. *Science, Technology & Human Values*, 40(6):1047–1076.

Debreu, G. (1954). Numerical representations of technological change. *Metroeconomica*, 6(3):45–54.

Frenken, K. (2006). A fitness landscape approach to technological complexity, modularity, and vertical disintegration. *Structural Change and Economic Dynamics*, 17(3):288–305.

Frenken, K. and Nuvolari, A. (2004). The early development of the steam engine: an evolutionary interpretation using complexity theory. *Industrial and Corporate Change*, 13(2):419–450.

Gorelick, L. and Gwinnett, A. J. (1981). The origin and development of the ancient near eastern cylinder seal. *Expedition Magazine*, 23(4):17–30.

Govindjee, Kern, J. F., Messinger, J., and Whitmarsh, J. (2010). *Encyclopedia of Life Sciences*, chapter Photosystem II. John Wiley & Sons.

Hansson, S. O. (2006). Defining technical function. *Studies in History and Philosophy of Science*, 37(1):19–22.

Hersch, P. and Zweibel, K. (1982). *Basic Photovoltaic Principles and Methods*. Solar Energy Research Institute, Golden, Colorado USA.

Koh, H. and Magee, C. L. (2006). A functional approach for studying technological progress: Application to information technology. *Technological Forecasting and Social Change*, 73(9):1061–1083.

Kroes, P. and Meijers, A. (2006). The dual nature of technical artefacts. *Studies in History and Philosophy of Science*, 37(1):1–4.

Laisk, A., Oja, V., and Eichelmann, H. (2016). Kinetics of plastoquinol oxidation by the q-cycle in leaves. *Biochimica et Biophysica Acta (BBA) - Bioenergetics*, 1857(6):819–830.

Makita, H. and Hastings, G. (2016). Modeling electron transfer in photosystem i. *Biochimica et Biophysica Acta (BBA) - Bioenergetics*, 1857(6):723–733.

Metcalfe, J. S. (2010). Technology and economic theory. *Cambridge Journal of Economics*, 34(1):153–171.

Miles, R., Hynes, K., and Forbes, I. (2005). Photovoltaic solar cells: An overview of state-of-the-art cell development and environmental issues. *Progress in Crystal Growth and Characterization of Materials*, 51:1–42.

Rasmussen, S. (2013). *Production Economics The Basic Theory of Production Optimization*. Springer Texts in Business and Economics. Springer-Verlag Berlin Heidelberg, 2 edition.

Rojas, J. B., Gómez-Lojero, C., and Salgado, P. H. (2016). La fotosíntesis: Subsistiendo bajo la luz del sol. *Avance y Perspectiva*. Retrieved from: http://ayp.cinvestav.mx/Publicaciones/ArtMID/4126/ArticleID/550.

Sahal, D. (1981). Alternative conceptions of technology. *Research Policy*, 10(1):2–24.

Saviotti, P. P. and Metcalfe, J. S. (1984). A theoretical approach to the construction of technological output indicators. *Research Policy*, 13(3):141–151.

Tikhonov, A. N. (2014). The cytochrome b_6f complex at the crossroad of photosynthetic electron transport pathways. *Plant Physiology and Biochemistry*, 81:163–183.

Vermaas, P. E. (2012). On the formal impossibility of analysing subfunctions as part of functions in design methodology. *Research in Engineering Design*, 24(1):19–32.

Vermaas, P. E. and Houkes, W. (2003). Ascribing functions to technical artefacts: A challenge to etiological accounts of functions. *The British Journal for the Philosophy of Science*, 54(2):261–289.

Vermaas, P. E., van Eck, D., and Kroes, P. (2013). The conceptual elusiveness of engineering functions: A philosophical analysis. *Philosophy & Technology*, 26(2):159–185.

Wagner, A. and Rosen, W. (2014). Spaces of the possible: universal darwinism and the wall between technological and biological innovation. *J. R. Soc. Interface*, 11(97):1–11.

Zhao, Z.-L., Zhou, S., Feng, X.-Q., and Xie, Y. M. (2017). Pump drill: A superb device for converting translational motion into high-speed rotation. *Extreme Mechanics Letters*, 16:56–63.