Serendipity: Towards a Taxonomy and a Theory

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Serendipity:

Towards a taxonomy and a theory

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Highlights:

- Serendipity can come in different forms and come about in a variety of ways.

- The Merton archives were used as a starting point for gathering literature and examples.

- We identify four types of serendipity together with four mechanisms of serendipity.

- Policy and theory implications vary by type and mechanism of serendipity.

- Serendipity does not necessarily strengthen rationales for basic research or weaken them for targeted research.

Abstract: Serendipity, the notion of researchers making unexpected and beneficial discoveries, has played an important role in debates about the feasibility and desirability of targeting public R&D investments. The purpose of this paper is to show that serendipity can come in different forms and come about in a variety of ways. The archives of Robert K Merton, who introduced the term to the social sciences, were used as a starting point for gathering literature and examples. I identify four types of serendipity (Walpolian, Mertonian, Bushian, Stephanian) together with four mechanisms of serendipity (Theory-led, Observer-led, Error-borne, Network-emergent). I also discuss implications of the different types and mechanisms for theory and policy.

Keywords: Serendipity, uncertainty, research policy, science policy, technology policy, innovation management.

JEL codes: O30, D80

1. Uncertainty, serendipity, and variety in serendipity

Almost all scholars who have studied research and innovation have noticed that uncertainties are involved: from economists (Nelson 1959; Arrow 1962) to historians (Rosenberg 1994; Edgerton 2007). They have observed that many, if not most, research and innovation efforts fail to achieve anything noteworthy (Rothwell et al. 1974; Freeman 1982; Petroski 2006). Attrition and the spectre of failure loom over basic and applied research, and exist in both science and technology (Vincenti 1990; Ziman 1994).

Where research does happen to yield something of value, the results are often quite different from what was expected. The term serendipity has been used to refer to this notion, that researchers make unexpected and beneficial discoveries (Merton and Barber 2004; Sampat 2014; Murayama et al. 2015). However, it should be apparent that serendipity can come about in a variety of ways and take different forms. Consider the following examples, all of which have been referred to as "serendipitous":

> a.   A measles outbreak in Indian monkeys caused poliomyelitis vaccine preparation to switch to African monkeys. This led Levine to discover the p53 tumour suppressor gene (Meyers 2007:p161).

> b.   Daguerre had spent years trying to coax photographic images out of iodized silver plates. After yet another futile attempt, he stored the plates in a chemicals cabinet overnight to find the fumes from a spilled jar of mercury accidentally produced a perfect image on the plate (Box 256; Roberts 1989:p49).

> c.   Richet, whilst searching for threshold doses of various poisons, discovered that he could induce sensitization to a toxic substance thereby developing understanding of allergies and anaphylaxis (Box 427). Accepting his Nobel Prize, he said, "It is not at all the result of deep thinking, but of a simple observation, almost accidental" (Roberts 1989:p125).

> d.   Elrich discovered Salvarsan, dubbed the first magic bullet, knowing very little about how it worked. It emerged from an extraordinary focus on the idea of chemotherapy (where chemicals might kill pathogens selectively).

Salvarsan was the 606th preparation, the 605 before it having each gone through their own set of experiments (Box 424; Meyers 2007:p62).

Clearly, the term serendipity is a label for a broad and multifaceted phenomenon. Levine and Richet were searching in one problem space (vaccinology and toxicology) when they came across their solutions for quite another (oncology and physiology, respectively). The same cannot be said of Daguerre and Elrich, who solved the same problems they were working on (photography and chemotherapy), though the way in which they arrived at their solution was unexpected (spillage, and trial and error). Richet places emphasis on 'simple observation', Daguerre on methodological error, Elrich on a committed hypothesis, and Levine on a network that allowed him to connect fields as far as vaccinology and oncology. Each of these emphases might have distinct implications for policy and theory.

In this paper, I aim to clarify the meaning of the term serendipity, principally by drawing attention to the heterogeneity of the phenomenon. I analyse "serendipitous" episodes to identify different types and mechanisms. Section 2 describes how I gathered my collection of examples and where I learnt about much of the existing literature on serendipity. Section 3 develops a typology of serendipity. Section 4 characterises some of the mechanisms by which serendipity may occur. Section 5 discusses potential policy implications, and the desirability and feasibility of measuring these types and mechanisms of serendipity. Section 6 concludes.

2. Research design: Merton as an unexploited source for serendipity

We are fortunate to stand on the shoulders of Robert K Merton, whose prolonged interest in serendipity led him to chart its lexicographical history and sociological semantics, a project that began in the 1940s and culminated with his posthumous book on serendipity with Elinor Barber in 2004. I spent six months in the archive that holds Merton's notes, most of which have not been published. It contains his detailed reading notes relating to serendipity, countless clippings from magazines, newspapers, and journals mentioning serendipity, and correspondence with scientists and sociologists of his day. From the Merton papers alone, I was able to hand-compile a qualitative database containing dozens of examples of serendipity and build an extensive bibliography with which I was able to find (hundreds) more examples of serendipity.

The Merton archive was a good place to start the search for varieties of serendipity, not least because it was he, as one of the "most influential sociologists of the twentieth century" (Calhoun 2010:pvii), who introduced the term into the social sciences.[1] The publication of Merton and Barber's (2004) book seems to have instigated much of the recent scholarship focusing on serendipity (e.g. Cunha et al. 2008; Murayama et al. 2015). Even publications that preceded Merton and Barber (2004) seem indebted to Merton's work or private communication with him (e.g. "Merton gave me an [unpublished] copy" (Andel 1994:p648)).

Merton, as a towering figure of sociology, had an extensive collegial network that was aware of his interest in serendipity. Merton was sent excerpts and examples of serendipity, one with a covering letter that revealingly noted, "I don't know what is serendipitous about this, but it appeared in American Airlines magazine" (Box 429:i4906). Merton himself acknowledged that many of these short anecdotes of serendipity are either understated or exaggerated, or apocryphal legends. Merton scrawled reminders down margins to check for authenticity, most of which went unanswered because he was unable to satisfy himself regarding their veracity.

However, for the purposes of building an initial typology of serendipity patterns, my requirement was only that the examples be potentially plausible. After screening the titles of the 513 manuscript boxes that comprise the archive for possible relevance to serendipity, selecting 38 boxes for perusal, and making detailed notes on 22 boxes and their subfolders, I identified examples of serendipity and references for further reading. I gathered them into a database totalling 118 examples, taking note of the main protagonist(s), what was discovered, a short (circa 60 words) description of how the discovery was made, and the sources used to compile the example.

The most common way the examples were reported was by discovery, a unit of analysis whose drawbacks I detail in section 5. Most discoveries were reported by multiple authors; these were recorded in the database as a single example. Consistency and variation in

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[1] Merton's interest in the 'unanticipated consequence of purposive social action' was published in 1936. His first published usage of the term serendipity was in 1945. Merton went on to define the term explicitly in 1948. These dates coincide with the start of its rapid diffusion according to Google Ngram, which charts the usage of any word found (in sources printed between 1800 and 2012, in the major languages, normalised by number of books published annually).

accounts of the same example allowed us to explore how the term serendipity was being applied rather than to establish reliability of the example in question through triangulation.

I coded the examples according to various characteristics because they initially appeared as similarities and differences. I drew on relevant literature by matching patterns identified with those reported by other authors. I iterated between the examples and emerging theory before settling on the motivations underlying the discovery and the outcomes of the discovery as two of the most important dimensions of serendipity. As a result, eight examples were dropped from the database following development of the typology.[2] I developed a typology based on these two dimensions, yielding four methodological ideal types (McKinney 1966; Bailey 1994; Doty and Glick 1994).

The next section will describe Walpolian, Mertonian, Bushian and Stephanian serendipity types and will highlight some of the examples reviewed as illustrative of each type. This is a conceptual rather than an empirical endeavour. Conceptually, a sphere and a plane touch at only one contact point, but empirically, allowances need to be made for the roughness of surface and the pressure of a real sphere on a plane. Such irregularities are lost when describing the ideal type because typologies are only instrumental and subordinate to the aims of the research. Since there is no such thing as a type independent of selective interests and the purposes for which it was developed, I make my interests and purposes explicit in section 5, outlining how they reside in certain research policy problems.

3. An illustrated typology of serendipity

I analysed hundreds of discoveries referred to as serendipity using a number of guiding questions. What are the similarities and differences across the examples, and between the various accounts of the same discoveries? How are authors (implicitly or explicitly) justifying their use of the term serendipity in their account? I found two consistently reappearing themes: the motivations underlying the discovery and the outcomes of the

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[2] These examples would be better described as co-incidental multiples rather than as serendipity. They are remarkable because the discovery was made simultaneously and independently, and this seems to be the sole basis upon which the word serendipity was used. (Though, Cozzens (1989) suggests that the term multiples may be an artefact of social control and co-ordination processes in science for resolving priority disputes over the degree of similarity between discoveries.)

discovery. They can help one to determine whether a discovery is serendipitous or not, and also serve as dimensions along which serendipitous discoveries may be distinguished as different ideal types. This section will describe the four types and will provide some of the examples reviewed as illustrative of each type.

3.1 Targeted search solves unexpected problem

Serendipity has been an inherently ambiguous word since its first documented use in 1754. Horace Walpole's whimsical reference to a tale about the Three Princes of Serendip combines accident with sagacity. Most pertinently, the Princes were making discoveries "of things which they were not in quest of" (Merton and Barber 2004:2). This forms the basis of our first type - **Walpolian** serendipity - discovery of things which the discoverers were not in search of - for which I can offer some of the most well-known discoveries as examples.

In 1897, whilst searching for a way of extracting proteins from bacteria for immunization, Buchner discovered that cell-free yeast extract could still convert sugar to alcohol and carbon dioxide. This discovery proved that whole cells were not necessarily required for fermentation and thereby inaugurated the field of enzymology (Kohler 1971; Box 378: i1652). In 1943, an explosion left soldiers exposed to mustard gas. Investigators were dispatched to find out whether it was an enemy bombing. Instead they found soldiers' white blood cell counts dropping. The link was made that perhaps mustard gas, or its derivatives, could treat cancers caused by the over-expression of white blood cells - modern chemotherapy was born (Meyers 2007:p123).

The most important features of this type of serendipity are the unanticipated and unexpected nature of the discovery, the fact that investigators were searching in one problem space but made their discovery in another.

3.2 Targeted search solves problem-in-hand via unexpected route

Merton's definition extended Walpole's conception of serendipity by asking not only what the original research motivations were, but also what the significance of the discovery was for further research.[3] By drawing attention to the outcome, Merton concludes that "Walpole's

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[3] "The pattern refers to the experience of observing an unanticipated, anomalous, and strategic datum which becomes the occasion for developing new theory" (Merton 1948: p506). Serendipity is one of four ways in which Merton notes that empirical research can influence theory (see Heinze et al. 2013: p830 for the others).

emphatic insistence that his term must be limited to discoveries that were not at all in quest of," - i.e. that no intended discovery can qualify as serendipity - means that Walpole's original definition "is too restrictive a concept of the role of serendipity in science" (Box428: i1594).

Thus, I distinguish **Mertonian** serendipity where the discovery may lead to the solution of a given problem via an unexpected route, as distinct from the more traditional type of serendipity where the discovery leads to the solution of an entirely different problem. Serendipitous moments in a research program might have played an incidental but significant role in the solution of a problem that was targeted from the outset.

Some well-known examples fit this type. By 1837, Goodyear had been searching for a decade for a way to make rubber thermostable, when he accidentally allowed a mixture of sulphur and rubber to touch a hot stove and discovered vulcanisation (Box 378: i1667; Halacy 1967). In 1948, Cade speculated that mania might be caused by abnormal metabolism of uric acid. He injected uric acid in the form of a lithium salt and observed dramatic therapeutic responses. However, it emerged that the uric acid part of the drug had nothing to do with its effectiveness. It was only the fact that a lithium salt of the acid was used that was responsible for the effect, other lithium salts were equally good (Box 427: i4873).

3.3 Untargeted search solves an immediate problem

There is a further direction in which I can build on Merton's definition to open up other types of serendipity. There may be no particular problem in mind, perhaps because the research is at an exploratory or basic stage and more concept formation may be needed to develop detailed hypotheses. Or, the professed goals and outcomes of the research may be so far away that the project objectives might as well be called un-targeted. Vannevar Bush claimed that pertinent discoveries "often come from remote and unexpected sources" (Bush 1945:p14; see also Balconi et al. 2010).

The defining feature of this **Bushian** type is that the discovery leads to a not sought-for solution because the research was un-targeted, or was not research at all. In an analogy to shopping, one may visit shops without intending to buy anything, but in the course of browsing be reminded of one's needs and how a product may serve those needs.

In 1879, as part of a research program into the general properties of sugar (as opposed to one with a specific goal), Fahlberg discovered saccharine, an artificial sweetener, after noticing a sweet taste on his hands (Box 427: i1634).[4] In 1895, Roentgen was preparing to recreate phenomena documented by Crookes, and tinker with them. In his emulation, he noticed a mysterious glow, a new form of radiation he called X-rays (Box 427; Box 378; Shapiro 1986).

Many drug discoveries also fit the Bushian type of serendipity. In 1844, Wells witnessed a man who, under the influence of laughing gas, injured his leg but claimed not to feel any pain; Wells used the compound as an anaesthetic thereafter. In 1947, Dr Gay prescribed a new antihistamine for a patient suffering from hives. The patient returned and reported that, "by the way, doctor, this is the first time I haven't become dizzy or nauseated on the ride to your office." (Box 424; Box 427: i1634, i4873). Dramamine became a motion sickness preventive. Similarly, in 1980, Minoxidil was being used as a treatment for high blood pressure when it was discovered to have hair retention and regeneration properties. Novocaine and Xylocaine were effective anaesthetics that were also discovered to be antiarrhythmic (Roberts 1989:p200).

However, such re-purposing of drugs approved for existing uses into *multi-purpose* drugs should be distinguished from *re-developed* drugs that were being developed for one use, but whose development path changed in favour of another use. The latter, re-developed drugs, would be Walpolian type serendipity taking effect before a drug has been approved. The infamous example is Viagra, which in the mid-1990s Pfizer was developing for angina, when clinical trials reported (besides its poor efficacy) that the drug could treat patients with erectile dysfunction. Another example is imipramine, an ineffective schizophrenia treatment found to work as an antidepressant (Box 424; Box 427:i4873). Note the way in which both these drugs remained single-purpose, which distinguish them from Bushian serendipity.[5]

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[4] He noticed that his sandwich tasted sweeter than usual, and returned to the laboratory where he tasted everything on his worktable—all the vials, beakers, and dishes he used for his experiments. He found the source: an overboiled beaker in which o-sulfobenzoic acid had reacted with phosphorus (V) chloride and ammonia, producing benzoic sulfinide. Though Falhberg had previously synthesized the compound by another method, he had no reason to taste the result. Once he tasted the value of the substance he took out a patent for it in 1885.

[5] It is possible for a drug fall into both categories at different times. For example, aspirin was first prepared as an antiseptic but was found to be ineffective and *re-developed* into an analgesic and antifebrile. It is now being investigated as a *multi-purpose* drug for suppressing tumors and cardiac arrest (Roberts 1989:195; Meyers 2007:149)

3.4 Untargeted search solves a later problem

Within un-targeted research, I believe there is another type of serendipity, whose defining feature is when un-targeted research comes upon a new unsought-for problem and unsought-for solution. Neither the problem nor the solution existed prior to the serendipitous episode. Paula Stephan describes it as "finding answers to questions not yet posed" (Stephan 2010: p232). **Stephanian** discovery serves to pique one's curiosity, even though it does not directly solve an immediate problem, and holds interest until it solves a later problem.[6]

In 1903, Benedictus dropped a flask. The flask shattered but he noticed to his surprise that the fragments of glass did not fly apart, the flask remained almost in its original shape. He found that it had a film on the inside to which the broken pieces of glass had adhered. He realized that this film had come from the evaporation of a solution of collodion (cellulose nitrate, prepared from cotton and nitric acid) which the flask had contained. After the incident, Benedictus learned of automobile accidents, with serious consequences from flying glass. This was the problem for which his solution was waiting, and his non-shattering flask became safety glass (Roberts 1989:p156).

In an another example, in 1820, Oersted was heating a wire by an electric current when he noticed that every time the current was switched on, a nearby compass needle was moved. When Oersted's reported this discovery, it caused a "stir" (Box 424; Kohn 1989:12) but did not immediately solve any conundrums; it was merely received as an interesting new phenomenon. However, the discovery would go on to solve problems that were yet to be formulated, a decade later, by the likes of Faraday and Morse who would identify electromagnetic induction and develop the telegraph system (Box 429:i4926).

3.5 Towards a taxonomy

In summary, one can conceive of at least four types of serendipity which emerge from the nature of the inquiry and the solution.

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[6] For Stephanian serendipity, one might invert Plato's well-known phrase, 'Necessity is the mother of invention', to 'Invention is the mother of necessity'.

		What type of solution did the discovery lead to?			
Is there a targeted line of enquiry?	Yes: Searching with a defined problem in mind	Solution of the given problem		Solution of a different problem	
		Mertonian serendipity		**Walpolian** serendipity	
	No: Searching with no particular problem in mind	Solution of a pre-existing problem		Solution waiting for a problem	
		Bushian serendipity		**Stephanian** serendipity	

Figure 1: A typology of serendipity in research.

The dimensions of this typology seem to resonate with other literature (Nightingale and Scott 2007; Stokes 1997; Senker 1991). In particular, the emphasis on outcome as well as motivation is consistent with Calvert's (2004) study of what constitutes 'basic research'. Her interviews with scientists and policymakers reveal different usages of the term and a range of views, which she categorised into six dimensions of variation. The two dimensions most frequently referred to by interviewees were epistemological (nature of the knowledge produced) and intentional (aims of research). Calvert argues that ambiguity over its meaning (i.e. choice over which dimensions to emphasise) gives the term its political character, and understanding the different reasons for defining in different ways could lead to a more enlightened discussion (2004:266). Whilst there are parallels that can be drawn for serendipity and its political economy, I do not mean to suggest that serendipity is restricted to, or synonymous with, basic science.

Basic and applied research categories may not necessarily be helpful or illuminating for studying serendipity. Findings that unexpectedly turned out to be very significant for basic science have often emerged from applied work on practical problems. Pasteur's work in the French wine industry helped establish bacteriology (Box 427), Carnot's efforts to improve steam engine efficiency helped to bring about thermodynamics, Bell Lab's efforts to remove static hiss from telephones helped to create radio astronomy (Box 424). Sometimes the switch between science and technology can be quite immediate (Nightingale 2014), suggesting that our discussion of serendipity can pertain to both.[7]

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[7] For example, in the serendipitous development of the pacemaker, Greatbatch and a physician were working to find a way to record heartbeats when Greatbatch happened to grab the wrong resistor. The error meant that the device was simulating the heartbeat, not recording it. The pacemaker was

Drawing boundaries between the quadrants in figure 1 is likely to be challenging in practice. In Merton's private notes, he alludes to this when he observes that "It seems customary to speak of serendipitous discoveries as though they were wholly unanticipated or accidental… [but] there are degrees of serendipity." (Box428: i1594). Though I distinguish between solutions for problems that were either given or wholly different, problems can in practice be partially solved, or partly abandoned in favour of another. With a drug, I may look to its formally approved indication to decide whether the problem solved was given or wholly different, but in most other cases such a convenient marker for sanctioned use may not be available. So the possibility that a discovery can displace or solve the original problem to differing degrees strikes us as an important feature of serendipity for empirical inquiry.

Similarly, whilst I distinguish between targeted and un-targeted search, in practice, lines of enquiry may be much harder to demarcate. One can have organisations and statistical categories dedicated to untargeted research, but there can still exist differing degrees of targeted enquiry. For example, Fahlberg's discovery of artificial sweetener was made as part of a research program that afforded him a broad and general remit, but if one takes note that the program was established and maintained by a sugar import company, the inquiry seems distinctly more targeted.

Although it may be difficult to separate out strict classes of serendipity by theoretical discussion alone, these two dimensions seem to be non-trivial. They provide us with at least four types of serendipity to help guide further empirical inquiry. McKinney (1966:p13) offers guidance on how this might be done: "The constructed type is a pragmatic expedient and does not purport to be empirically valid. The main purpose it serves is to furnish a means by which concrete occurrences can be compared, potentially measured, and comprehended. The comparison and measurement of empirical approximations reveal nothing but deviations from the construct. This is not only to be expected, but is to be sought after, for it is the basis of the value of the typological method. These deviations will be relative… If degree of deviation is to be determined repetitively and comparatively, then the base measurement (the type) must be held constant. The relations between the elements (criteria) of the type are postulated relations; therefore they may be legitimately be held constant".

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deployed, less to record and study the heartbeat than to intervene and offer a technological therapy for those with an irregular heartbeat.

In the next section, it is these "relations between the elements (criteria)" that I explore as underlying mechanisms of serendipity. In doing so, I address Doty and Glick's (1994:p230) concern that "most typological theories are inadequately developed because the causal processes operating within each type are not fully specified" leading to "over-emphasis on describing the typology and under-emphasis on developing the theory" (Doty and Glick (1994:p231).

4. Factors and mechanisms of serendipity

I suggested that serendipity can be identified by examining research motivations and research outcomes, and may take one of four types: Walpolian, Mertonian, Bushian and Stephanian. However, the typology tells us little about the mechanisms underlying these serendipity types. In my search for mechanisms, I compared hundreds of examples of serendipity for similarities and differences that help to describe how serendipity happens. Unlike types of serendipity, which were mutually exclusive (and whose boundaries were somewhat blurry), I believe each of these mechanisms of serendipity is to a degree necessary (none are likely to be sufficient on their own).

Four consistently reappearing themes emerged from the comparative analysis. Serendipity may be theory-led, observer-led, error-borne or network-emergent. Serendipity may become conspicuous because the growth of theory makes it stand out to any given observer; or serendipity may be observable only to some with certain tools, techniques and attributes; or serendipity may emerge following methodological deviations, errors, and spillages; or serendipity may involve a network of actors. This section will describe the four mechanisms in more detail and provide some of the examples reviewed as illustrative of each mechanism.

4.1 Serendipity and theory

This mechanism is about the idea that serendipity requires deviation from theoretical expectations. Without some contrast to theory an event cannot be serendipitous, it is mere chance.[8] Louis Pasteur considered chance to be a subordinate of theoretical advance:

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[8] As Keynes (1921:p10) noted, "I say, if a coin falls head it is 'by chance', whereas its falling heads is not at all improbable… The fall of the coin is a chance event if our knowledge of the circumstances of the throw is *irrelevant* to our expectation of the possible alternative results. If the number of

"Without theory, practice is but routine born of habit." (Radot, cited in Merton and Barber 2004:p162). Pasteur illustrates with his account of telegraph development, and in doing so makes one of the most quoted remarks about serendipity.

> "Oersted held in his hands a piece of copper wire, joined by its extremities to the two poles of a Volta pile. On his table was a magnetised needle on its pivot and he saw (by chance you will say, but chance only favours the mind which is prepared) the needle move and take up a position quite different from the one assigned to it by terrestrial magnetism."

Theory or experience allows any given observer to identify the serendipitous episode as being incongruent with predictions and expectations. A 1963 Science article (Box 378; i1641) describes the theoretical lead-up to the discovery of uranium fission:

> "The experimenters had posed an interesting, clear-cut question, 'Is radium a product of irradiation of uranium?' They devised an appropriate set of experiments to answer the query. The result was certain to be important, whatever it was. If they had proved that radium was a product, the result would have been considered very important, though not so significant as what they actually found." (p1177).

A more recent example is the discovery of angiostatins: Folkman was investigating potential substitutes for blood in transfusions when he observed that tumors often stopped growing when they were quite small (Meyers 2007:p145). He theorised that tumors needed to develop their own blood vessels to grow bigger. The search for blood vessel growth inhibitors was now a given when Folkman's team noticed a fungus that had contaminated a culture dish of endothelial cells and arrested their growth. A second more effective inhibitor was discovered by a chance encounter at a conference. As Pasteur might have noted, chance played a subordinate, if not subsequent, role to theory development in this episode. The growth of theory may guide the observer on where to look, restricting the scope for their possible observations and inferences.

4.2 Serendipity and individuals

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alternatives is very large, then the occurrence of the event is not only subject to chance but is also very improbable…".

Even within a given scientific or technological paradigm (Kuhn 1962, Dosi 1982), there is a varied distribution of skills, techniques and talents across individuals, and unequal access to different kinds of equipment, instruments and other resources. I discuss two factors, observation routines and instrumentation, that may affect an observer's perceptiveness (variation in what individuals notice). These stand as possible factors of serendipity distinct from the prepared mind theme discussed previously.[9]

Individual attributes may affect perceptiveness for serendipity. For example, in 1912, Ramsey demonstrated his newly discovered gases by passing an electrical charge through them to show their vivid colours. It was only Claude, seeing the same experiment as the 500 or so who also heard the lecture, who realised its commercial importance as the first neon light (Box 256: i1733). Similarly, many scientists had operated on the African frog whose skin contained the antimicrobial magainin, but it was only Zasloff who noticed it (Roberts 1989:p169). Another example is the discovery of gut bacteria and peptic ulcers by Warren and Marshall, made despite the prevailing view of gastroenterologists (Meyers 2007:105).[10]

Routines and systems for observation might support serendipity in some individuals rather than others. Darwin is admired not only for his eponymous theoretical contributions but also for the way he systematically documented his observations, recording even the most trivial of his musings, and for curating and cataloguing a vast collection of specimens. Ecologists and astronomers pay particular attention to cataloguing what they observe. Pathologists have a systematic approach to examining a corpse, a system so prized that the completeness of

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[9] Most science and technology studies scholars subscribe to the idea that observations are never completely free from theoretical framings and are, to some extent, 'theory-laden' (see Hess 1997). But, by expressing their claims in matters of degree, they also leave open the possibility of observations that are weakly framed by theory.

[10] Specialists at the time thought that no bacteria existed in the guts after biopsies failed to reveal any bacteria. Warren noticed large numbers of bacteria in biopsy samples of patients with gastritis, and that the stomach cells near the bacteria were damaged. Warren struggled to attract attention from gastroenterologists to his finding. Marshall, a resident doctor on gastro-rotation, initially noticed that bacteria were clinically relevant when he treated a gastritis patient successfully with antibiotic. So he tried to culture the bacteria for characterisation and testing. He thought the spiral bacteria were of the campylobacter genus, which grow in two days. On this basis, the lab discarded agar plates after 48hrs if no growth was visible. After months of failed attempts at culturing the bacteria, Marshall left for the Easter weekend and the plates were inadvertently left in the dark humid incubator for 5 days. Marshall returned to find the culture growing (Meyers 2007:105).

observation might even be considered by some to take precedence over establishing cause of death.[11]

For example, Warren who discovered gut bacteria, was a pathologist sensitised not to current theory on gastroenterology but to bacteria repeatedly cropping up in biopsy. In an example where a nurse noticed that jaundiced infants placed near the window in the sunshine recovered faster, she did so in a hospital - a highly observed and structured environment (Roberts 1989:p136). The nurse was presumably in the habit of reporting her observations to others as part of her profession, her report was followed up and UV light for neonatal infants is now standard. Similarly, in another example, insulin was discovered when a technician noticed the swarm of flies that gathered around the urine of pancreas-less animals (because it was later found to be loaded with sugar) (Box 378:i1666; Box 424). So, in various forms of inquiry, one can see that traditions, systems and protocols for observation have emerged. In the cases of the pathologist, nurse and technician noted above, it was not so much theory as it was the observation system that helped them to notice their discoveries.

Observations are usually mediated by instruments, and the development and use of instruments themselves play an important role in serendipity. This is not necessarily the testing of theories nor the replication of experiments, but rather the trying out of new practices. Price (1984) notes that a great deal of laboratory work involves practicing old techniques, tinkering and fiddling to produce a new technique or 'research technology' (Joerges and Shinn 2001), then using it on everything in sight. Such work, without being strongly anchored to any particular theory, means "experimentation has a life of its own" (Hacking 1983:p250), and occasionally, the experimenter will produce qualitatively new effects (Rheinberger 1997). Heinze et al. (2013) offer evidence for this line of thought with a sophisticated analysis of the follow-up research to two Nobel Prize-winning breakthroughs.

Instruments can be developed and used quite free from theory, playfully even. Fleming, for example, would streak his agar plates with bacteria that would yield different coloured colonies, allowing to him to 'play' with different patterns that would emerge after incubation (such as a Union Jack, rock-gardens, a mother feeding a baby) (Box 427). Nylon was discovered at Du Pont whilst attempting to develop artificial silk, but seemed initially to lack

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[11] "Being thorough is essential… with cancer resections for example a specific format is in place when reporting results to avoid missing important information." (personal communication 2015, Mr Patel, vascular surgeon).

useful properties. Whilst playing around with the material however, specifically running down the hall whilst stretching it out, useful properties were found (Marvel 1981).[12] When Langmuir discovered gas-filled lamps, it was by playing around with bad vacuums rather than by diligently improving them, and in using different gases to see how bad they made the lamp, he discovered better performing lamps (Box 256: i1732).

The use of instruments by individuals unaware of prior theoretical predictions can be the basis for serendipity. Astronomers Baade and Zwicky predicted pulsars three decades before their discovery, and physicist Gamov predicted cosmic microwave background radiation two decades before its discovery – both predictions needed to wait for observers equipped with suitably developed instrumentation for validation (Box 424). The observers' lack of awareness of prior predictions is what made their discoveries serendipitous. This contrasts with the discovery of the Higgs-Boson particle, which also had a long interval between theoretical prediction and empirical validation but was non-serendipitous because the search effort was dedicated to the theoretical prediction.

4.3 Serendipity and the tolerance of error

Inquiry can be loosely directed, allowing errors to seep in to experimental design whilst also hoping those very errors will be a source of serendipity (Box 428). The physicist Max Delbruck nonchalantly dubbed this the principle of 'limited sloppiness' (Salvador Luria similarly called it 'controlled sloppiness' and Root-Bernstein (1988; Box 427:i4883) refers to the making of 'intelligent mistakes').[13] For Luria, if a parameter is varied accidentally, one might be able to track down any unexpected results back to that variation. "It often pays to do somewhat untidy experiments, provided one is aware of the element of untidiness. In this way, unexpected results have a chance to come up. When they do, I can trace their cause to

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[12] Hill noted that if he gathered the polymer with a glass stirring rod and drew it out of the mass, it extended and became silky in appearance. Hill and his colleagues wanted to see how far they could stretch one of these samples, and ran down the hall. In doing so, they realised they were orienting the polymer molecules and increasing the strength of the product into something more useful (Marvel 1981).

[13] "Many scientists had irradiated bacteria and phage with ultraviolet light and measured survival rates. It turns out that if you measure survival in the presence of daylight, then you get entirely different values than when you measure survival in the dark or in red light. The reason it hadn't been discovered was because whoever had done the measurements had done them very carefully under controlled conditions, always the same light. Kelner and Dulbecco had done the experiments in a more sloppy way, sometimes putting the plates here, and sometimes there, sometimes having the water bath near the window and sometime not near the window" (Harding 1978).

the untidy, but known, features of the experiment." (Luria 1955, in Merton and Barber 2004:192)

Mistakes play a prominent role in accounts of serendipity, where seemingly critical substances have been dropped or spilled. See for instance Nobel on dynamite, Kolliker and Muller on electro-cardiac activity, Hyatt on celluloid, and Chardonnet on artificial silk (Box 256; Roberts 1989; Meyers 2007). Substances have been inadvertently heated or exploded in serendipitous episodes. For example, Goodyear on vulcanisation, Stookey on ceramic glass, Davison and Germer on electron waves, and Elrich on bacterial staining (Halacy 1967:p73; Box 256: i1727; Box 424:7). Serendipitous episodes have also emerged after substances were forgotten about in pockets, or laid to rest over vacations. For example, Spencer and the microwave oven, Becquerel and radiation treatment for cancer, Fleming culturing penicillin, Pasteur attenuating vaccination, Becquerel noticing radioactivity, and Marshall culturing gut bacteria (Box 378: i1650 and i1664; Box 427; Halacy 1967). Contamination, methodological blunder and equipment malfunction also feature frequently in accounts of serendipity, as well as assumed equipment failure. For example, Fleming's lysozyme and penicillin, Warren's gut bacteria, and Folkman's angiostatin, Dotter's angioplasty, Furchgott's vasodilation, Vorhees' vascular stents, Galvani and Volta's battery, Nicholson and Carlisile on water structure, Swallow and Perrin's polythene, Fox's polycarbonate, Bell and Watson's telephone and Penzias and Wilson's background radiation (Box 256; Box 378; Box 424; Box 427; Box 429; Roberts 1989; Meyers 2007).

4.4 Serendipity and networks

There are at least three ways in which networks are pertinent for serendipity. Firstly, networks play an informational role, bringing discoveries to the attention of researchers who can exploit them. Secondly, networks play a teamwork role, where exploitation of an observation may require the skills and resources of multiple people. Thirdly, networks could discourage serendipity via 'groupthink' or 'echo-chamber' effects.

There is a growing body of literature indicating that a researcher's output, both in terms of quantity and quality, is related to their position within a collaborative network (Balconi et al. 2004; Rotolo and Petruzzelini 2013). The strength of weak ties may govern exposure to novelty (Granovetter 1973) and opportunities to broker information and resources from certain points within a network may offer a locus for serendipity to emerge (Burt 2004).

Scholars embedded in more diverse research networks may be more likely to recognise and pursue serendipitous discoveries simply because they have more information to hand, or more likely, know where to go in order to source the information.

In the case of the background radiation discovery, Penzias and Wilson could only make sense of their results after contacting physicists (Box 424). A more recent example is that of Agre, who was trying to isolate and characterise the Rh blood group antigen when a second protein kept appearing in the tests (Dreifus 2009). Initially, it was considered a contaminant or a breakdown by-product of Rh isolation, but it showed up in all types of cells. Agre proved that this other protein was in fact a cell membrane channel protein after he visited his haematology professor, who suggested that as the explanation.

In addition to information exchange, there is an also a teamwork role that networks play. In his 1933 essay on the craft of experimental physics, Blackett suggests craft specialty may restrict the scope for serendipity:

> "The experimenter is always a specialist and does not often change his
> technique... Often he cannot usefully do so, for there are few experiments
> which do not need a considerable apprenticeship." (Box 378: i1685).

However, co-ordination might render it unnecessary for all researchers to have a disposition for serendipitous discovery. We have known since the 16th century that specialised investigators of a variety of skills and abilities could conceivably come together in a fruitful division of labour.[14] Mering and Minkowski may have demonstrated the function of the pancreas in diabetes by creating experimental diabetes, but it was their technician who noticed the flies loitering around the urine of pancreas-less animals (Box 378: i1666; Box 424). Similarly, it was Hunt who noticed the mouldy cantaloupe, before Florey, Chain, Merck and Pfizer developed it into high yielding penicillin (Box 378: i1648).

Fruitful collaborations can occur between individuals in quite disparate parts of the network, across industrial sectors even. Discoveries of polythene and Teflon involved the telecommunications industry and the military as well as the chemical industry (Roberts

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[14] Francis Bacon's dreamt up research organisation, the House of Solomon, included Merchants of Light, who keep up with the work of other organisations, Mystery-men who gather up earlier experiments into the state of the art, Pioneers who try new experiments, Lamps who direct experiments, Inoculators who execute experiments with proficiency of technicians, and Interpreters of Nature who raise former discoveries into greater axioms and aphorisms.

1989). Streptomycin and viral transmissibility of cancer were discovered after agricultural poultry farmers contacted Waksman and Rous (Box 378:i1647; Meyers 2007:p157). The systemic nature of some discoveries is noticeable in healthcare, where doctors, patients and researchers come together from multiple sectors in serendipitous discovery of drugs such as abatecept, minoxidil, imipramine.

Lastly, networks that are particularly homogeneous, cohesive and insular may be inversely related to serendipity. Since social psychologists have explored 'groupthink' or 'echo-chamber' effects in various contexts (Janis 1972, cited in Turner and Pratkanis 1998; Esser 1998; Sunstein 2001), it is plausible to think that such effects can occur within research collaborations too. For example, large collaborations may suffer from pressure to pursue a least-publishable-unit strategy where members want a large number of incremental papers or where each wants a turn as first- or corresponding-author. These are tricky ideas to test (Katz and Martin 1997), but amidst the rapidly burgeoning literature on research collaboration there are signs that not all connections would facilitate serendipity (see Bozeman et al. 2016 and references therein).

4.5 Expansion and reduction to a typology of serendipity and its mechanisms

The four serendipity mechanisms characterised above were mapped onto the typology to see if any preliminary patterns emerge. Cursory examination indicates that types and mechanisms are independent (Chisquared=10.82, p=0.28). However, such an analysis precludes the possibility of different combinations of mechanisms varying systematically by serendipity type (moreover, as described in section 2, the examples were not subjected to proper empirical verification).

Developing a further typology offers the benefit of being able to visualise different combinations of mechanisms underlying the serendipity types, help interrogate the assumptions behind them, and explore interaction effects, if any. By identifying four dimensions of research underlying the serendipity types, we have already completed the first step of what Paul Lazarsfeld (1937, cited in Bailey 1994) calls "substruction". For the remainder of the process, we can extend the dimensions to a full typology, as in figure 2, and then engage in "functional reduction", "pragmatic reduction" or "arbitrary reduction" (Lazarsfeld 1937, cited in Bailey 1994).

Figure 2: A sixteen cell typology formed by "substruction" from four dimensions of serendipity mechanisms

		Mechanism 3: **Error**			
		Present (1)		Absent (0)	
Mechanism 1: **Theory**		Mechanism 4: **Network**		Mechanism 4: **Network**	
		Present (1)	Absent (0)	Present (1)	Absent (0)
Present (1)					
	Mechanism 2: **Individual**				
	Present (1)	(1,1,1,1) **1**	(1,1,1,0) **2**	(1,1,0,1) **3**	(1,1,0,0) **4**
	Absent (0)	(1,0,1,1) **5**	(1,0,1,0) **6**	(1,0,0,1) **7**	(1,0,0,0) **8**
Absent (0)					
	Mechanism 2: **Individual**				
	Present (1)	(0,1,1,1) **9**	(0,1,1,0) **10**	(0,1,0,1) **11**	(0,1,0,0) **12**
	Absent (0)	(0,0,1,1) **13**	(0,0,1,0) **14**	(0,0,0,1) **15**	(0,0,0,0) **16**

In order to satisfy taxonomic requirements (that types need to be exhaustive and mutually exclusive), we will have to assume that it will be possible to classify the mechanisms in a binary way. Each cell in Figure 2 is labelled in terms of presence (coded 1) or absence (coded 0). Thus, the type in cell 1 possesses all four dimensions (1,1,1,1), and might reasonably be called an 'ideal' type, while the type in cell 16 possesses none (0,0,0,0). The pair of cells 4 and 13 are also polar types, but are not quite as extreme as cell pair 1 and 16. The interior cells (cells 6, 7, 10 and 11) might be described as least extreme, since they differ from all other cells by no more than two dimensions, though there is no reason to think this means they will be most prevalent empirically.

The 16 types of mechanisms for 4 types of serendipity (64 forms!) may be too unwieldy to be manageable, and could benefit from some reduction (Lazarsfield 1937). Cell 16 can be dropped on "functional" grounds, since no cases of serendipity are likely to be found where none of the underlying mechanisms are present. We might collapse the middle two rows on "pragmatic" grounds, if I make the assumption that theory and observation are two sides of the same coin, such that cells pairs 5 and 9, 6 and 10, 7 and 11, and 8 and 12 are merged. Or if, as I suggested earlier, we assume that none of the mechanisms are likely to be sufficient on their own, we might then eliminate on "arbitrary numerical" grounds cells that do not have at least two mechanisms present (cells 8, 12, 14, and 15).

5. Serendipity: Implications and (mis)measurement

The previous sections characterised four types of serendipity (Walpolian, Mertonian, Bushian, Stephanian) together with four mechanisms of serendipity (Theory-led, Observer-led, Error-borne, and Network-emergent). The types help us to appreciate that serendipity may exist across the research system in various forms. The mechanisms suggest that serendipity is not random; there may be important combinations of factors affecting its occurrence and scope for altering its prevalence.

In this section I explore implications for policy and theory, and suggest that they are likely to vary for different forms of serendipity. Measurement of these different forms of serendipity may help underpin policy with stronger rationales, but this would entail addressing some difficult conceptual challenges.

5.1 Serendipity: Some implications of variation for theory and policy

The notion of serendipity has played an important role in debates about the feasibility and desirability of targeting R&D investments, and in theories about the rate and direction of scientific and technical change (Sarewitz 1996; Stirling 2008; Mowery et al. 2010). Vannevar Bush invoked serendipity to argue against targeting research to specific goals in his blueprint for post-war science policy.[15] Similarly, some influential scientists and philosophers of science have argued that science cannot be planned and should be left to self-organise (Polanyi 1962; Ziman 1994). Such views stand in contrast to others who argued that research can and should be directed to social needs (Bernal 1939; Soddy 1935, cited in Guston 2012; Sarewitz 2016). In such debates, defences of basic science often deploy the notion of serendipity under the assumptions that serendipity is prevalent and that serendipity provides unequivocal support for basic science rationales.

However, the existence of variety in serendipity, as shown in this paper, brings these assumptions into question. The policy implications seem more variable than simply associating serendipity with less research targeting. For example, the possibility of Mertonian

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[15] Bush (1945:12-14) asserts "Scientific progress on a broad front results from the free play of free intellects, working on subjects of their own choice, in the manner dictated by their curiosity for exploration of the unknown. Freedom of inquiry must be preserved under any plan for government support of science… Many of the most important discoveries have come as a result of experiments undertaken with very different purposes in mind… the results of any one particular investigation cannot be predicted with accuracy."

serendipity, where targeted search solves the problem-in-hand via an unexpected route and where unexpectedness lies in the approach and not the finding, suggests that serendipity and research-targeting are not necessarily at odds with each other.

So the distribution of serendipity across the different types may turn out to be more significant than its overall prevalence. Previous sections have shown that serendipity is not confined to untargeted research (the Bushian and Stephanian types). There are also Walpolian and Mertonian types of serendipity, which can arise from applied research and technological development activities. If serendipity is just as prevalent in targeted research as it is in untargeted research, the rationale for basic science seems to be weakened.

The breadth of serendipity is at least as important as its prevalence, both in terms of sources and impacts. The implications of crossing over from microbiology to pathology are quite different from crossing over from physics to biology. Measures of epistemic distance (e.g. interdisciplinarity, Rafols et al. 2012; Leahey et al. 2016) would seem to be useful here, as well as an understanding of why the flow of traffic is so heavy along some routes (e.g. physics instrumentation into medicine, lasers, x-rays, MRI scanners, see Rosenberg 1992; 2009). Additionally, the impact of a few serendipitous discoveries may be more significant and foundational in their nature for subsequent discoveries than a high number of other serendipitous discoveries. In short, magnitude of serendipity may be more deserving of attention than frequency. The tangled birth of textile, chemical and pharmaceutical industries is indicative of the possibility that the cumulative contribution of just a handful of serendipitous discoveries to socio-economic change could be very large.[16] Evidence in support of either of these possibilities could strengthen the rationale for untargeted research.

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[16] There could be eight counts of serendipity here, perhaps more depending on how one is to count serendipity, as explored in 5.2: Local custom had it that a man could recover from fever after drinking from a pool which had extracts from a neighbouring quina tree [#1]. Soaring demand for the bark of this Peruvian tree led to the isolation of its antimalarial active ingredient, quinine, in 1820. By the 1850s, Perkin was one of many fervently searching for a synthetic version of quinine, when he stumbled upon coal tar dye [#2]. In the 1890s, when Elrich discovered that dyes could attach to bacteria and selectively stain them, he was prompted to consider the possibility of using chemicals to selectively kill pathogens [#3]. (This idea, chemotherapy, was vital for motivating the search for antibiotics and their development.) In the 1920s, Domagk and others were hired to test a range of synthetic dyes for their effectiveness against disease. They found dyes that were indeed bactericidal, but it was the sulfonamide group in them that was essential [#4]. (The dye was merely incidental, and indeed the red tinge that some children had acquired was in retrospect needless.) By then, Koch had developed selective bacterial culturing techniques, after noticing a slice of old potato with different coloured spots [#5] (previously, bacteria were cultured in flasks of nutrient broth). In the 1920s, these were the techniques that Fleming found himself playing around with, when a drop from his runny

The scale and scope of serendipity also affects our economic rationale for public funding of basic research. Early work focused on weak incentives to invest in research due to its low appropriability (Nelson 1959; Arrow 1962). The private actor may have undertaken research, and then not been able to exclusively exploit the results without a rival party (free-rider) benefiting. However, the assumption that private actors would not be able to appropriate all the benefits arising from the fixed costs of their R&D investments was not only due to the risk of free-riders, but also because the research itself might not yield what was expected. The results could also be so unexpected that the private actor could not make sense of them and exploit them, whilst the rival party could. If the unexpected outcome took the form of results that could not be exploited by the private actor but could be serendipitously exploited by others, the disparity between private and social welfare is substantially larger than is the case where only free-riders are concerned.

There is overlap here with the oft-discussed concept of R&D spillovers. Much of the literature has tended to refer to spillovers when research undertaken by one organisation is used by another organisation. Especially when the organisation in question is a firm, the spillover concept has been useful for economists of innovation concerned with competition, industry structure, and rates of return to R&D (Jaffe 1989; Cohen et al 2002; Hall et al. 2010). Especially when the organisation in question is a university, the spillover concept has been useful to geographers of innovation interested in spatial clustering, regional planning and different forms of proximity (Breschi and Lissoni 2001; Bresnahan et al. 2001; Boschma 2005; Frenken et al 2007). Whilst it is plausible that such knowledge flows could also apply to serendipity, it seems worth noting that serendipity can occur not only between organisations but *within* them too (as exemplified by Viagra, whose re-directed development occurred largely within the boundaries of a single firm). As such, serendipity may be pertinent for management and organization theory: for example, "solutions looking for a question" in the garbage can model (Cohen et al. 1972:p3); entrepreneurship as little more

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nose fell on a petri dish and lysed some colonies of bacteria [#6]. His discovery of lysozyme put him on alert for noticing the 'contaminant' that later turned out to be penicillin [#7]. In the 1940s, Florey and Chain, with the help of Merck and Pfizer, helped to realise its commercial potential as a powerful antibiotic that could be mass-produced. They were able to do so only after Mary Hunt, a laboratory aide, brought in yellow mould she happened to notice growing on a rotten cantaloupe in a fruit market, which turned out to be 3,000 times more potent than Fleming's original strain [#8]. (Box 256; Box 378; Box 424; Box 427; Meyers 2007; Greenwood 1992).

than a random walk (Coad et al. 2015; Liu and Rond 2016); and infrastructures for the emergence of complex products like drugs (Dougherty 2016:p8; Gittelman 2016:p1573-4).

The possibility of serendipity occurring through a variety of mechanisms should raise concerns among those seeking greater efficiency in research, and those framing innovation solely in terms of reducing uncertainty. The pursuit of efficiency could be supressing the error-borne serendipity mechanism described in the previous section, and driving out diversity in methodological approaches needed for Mertonian serendipity to come about. Emphases on efficiency, in combination with a shift towards funding at the project-level, might also make it harder to recognise and appreciate that it is possible for research to unexpectedly solve a later problem (the Stephanian type of serendipity), where research may initially appear to have little utility and be deemed inefficient.[17] The bureaucratisation of research makes the role of teams, networks and funding pertinent for questions about whether serendipity remains feasible or even desirable (Heinze et al. 2009; Azoulay et al. 2011; Lee et al. 2015; Walsh and Lee 2015).

In short, different forms of serendipity could have different implications for policy and theory. Figure 3 offers a preliminary elaboration of this idea. Further study into serendipity should be guided by the possibility that considerable field-specific differences exist. Theory-led and observer-led serendipity mechanisms suggest that the distribution of serendipity across fields of enquiry may be uneven. At the early stages of science, "the pickings may be easier" (Hollingsworth 2008: p330) when theory may be ripe for serendipitous discovery, as Hooke, Priestly, Mach, Planck and others have noted (Merton and Barber 2004:p160). It may be that serendipity is more prevalent in interdisciplinary research and nascent fields of research (Merton and Barber 2004:p45; Yegros et al. 2015). Highly empirical research fields in the natural sciences (such as astronomy, organic chemistry, medicine, and technology) may exhibit a prevalence of serendipitous episodes not seen in the social sciences (after

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[17] Some impacts emerge mostly over the long term. This implies the need for a trained workforce to maintain the knowledge base within which indirect serendipitous links can eventually be forged. "Scientific knowledge is indeed durable, but only at the price of the heavy investments needed to maintain it. In order to make the law $f = m\,a$ available in Singapore in 1993, a large number of textbooks had to be published and sold, teachers had to drum the message into stubborn heads, research institutions and enterprises had to develop, researchers had to be trained and paid. Compared to the cost of maintaining a so-called universal law, the cost of maintaining the American army in Kuwait pales into insignificance." Callon (1994:p406).

taking into account that discoveries of any sort seem to feature less prominently in the social sciences).

Figure 3: Serendipity types and mechanisms: some implications for theory and policy

Serendipity types and mechanisms	Some implications for theory and policy
Walpolian type • Targeted search solves unexpected problem	• Additional economic rationale for public funding of research (Nelson 1959; Arrow 1962) • Emphasises a broad remit for mission oriented agencies
Mertonian • Targeted search solves problem-in-hand via unexpected route	• Co-production of knowledge; Mode 2 and Triple helix models (Gibbons et al. 1994; Etzkowitz and Leydesdorff 2000) • Emphasises diversity in methodological approaches
Bushian • Untargeted search solves an immediate problem	• Linear model; new economics of science (Balconi et al. 2010; David et al. 1999) • Emphasises diffusion of knowledge across a variety of distinct institutional settings
Stephanian • Untargeted search solves a later problem	• Economic history of technology, innovation studies (Rosenberg 1994; Pavitt 1999) • Emphasises maintenance of the knowledge base, indirect links from research, and long-term impact; limits to impact-based funding
Theory-led • The growth of theory makes serendipity conspicuous to any given observer	• Philosophy of science and technology (e.g. Kuhn 1962; Dosi 1982) • Emphasises variation in serendipity across disciplines; research field specific funding
Observer-led • Serendipity is observable only to some with certain tools, techniques and attributes	• Sociology of science and technology (e.g. Merton 1973; Bijker et al. 1987) • Emphasises variation in serendipity across actors; people-based funding
Error-borne • Serendipity may emerge following methodological deviations, errors, and spillages	• Normativity and prescriptiveness of research methods • Emphasises tolerance of error and controlled sloppiness in research performance
Network-emergent • Serendipity may involve a network of actors	• Weak ties and structural holes (Granovetter 1973; Burt 2004) • Emphasises variation in serendipity across networks; consortium-based funding

5.2 An amorphous unit of analysis: Challenges to measuring serendipity

I have explored some of the possible motivations for measuring serendipity. Here, I discuss some of the conceptual challenges likely to be encountered in measuring serendipity. They relate to timing and sources of exaggeration and suppression of serendipity.

Serendipity may depend on the window of analysis. For example, if I were to take only the moment that Goodyear accidentally dropped sulphur and rubber into a hot stove, I might be tempted to be classify his discovery as untargeted research that unexpectedly solves an

immediate problem (the Bushian type). But putting the episode into context would reveal it to be of another type of serendipity, because for ten long years he had ceaselessly worked on the problem of vulcanisation (Box 378: i1667; Halacy 1967). By changing our timeframes, I find Goodyear was searching with a defined problem in mind and the route to the solution was merely incidental (Mertonian serendipity).

The long-term impacts of serendipitous discoveries also make analysis and classification difficult. For example, in the discovery of Teflon, Plunkett was searching for a non-toxic refrigerant, when he discovered a polymer without use (because it was too expensive); this would be Stephanian serendipity. It then solved a different problem, for developers of the atomic bomb (who needed gaskets that would resist the corrosive gas used to produce U235); this would be Walpolian serendipity. It took decades before better known impacts emerged (cooking utensils, transplants, pacemakers, spacesuits and so on), and if I were to include these solutions, I am still led to classify the serendipity as Walpolian, despite the fact that these solutions are completely different to the original instance of Walpolian serendipity.

Similarly, to describe the Friedel-Crafts procedure as a discovery where the search for a solution to one problem led to the solution of another (Walpolian serendipity), would be to severely understate the vast array of 'other' solutions emerging in the years that followed (still Walpolian serendipity, but more so). If one broadens the timeframe for analysis, perhaps no other organic reaction has been of more practical value (gasoline, artificial rubber, artificial detergents, etc). In another example, the discovery of polythene was developed for insulating radar cables but was then developed into an array of other products ranging from cars to carpets.

The difficulty of defining markers for the start- and end-points of a serendipitous episode is exacerbated if we take seriously the notion that researchers may have latent interests as well as active ones. The way we treat latent questions as either having had 'a defined problem in mind' or 'searching with no particular problem in mind', depends on the investigator's work on antecedent problems. The type of serendipity becomes contingent on our recognition of whether the issue was at the forefront of the investigator's concerns.

The notion of a hunch allows investigators to post-hoc claim they had some sort of intuition, preceding a serendipitous episode. For example, Kerkule reported that his two most important discoveries, the idea that atoms combine relative to their valence and the structure

of benzene, came to him in dreams (Roberts 1989:p75). Another example is Senefelder, who on a hunch treated his limestone slab with acid to discover lithography (Halacy 1967:p99). Such notions are impossible to verify, akin to the lottery winner who claims that she 'knew all along' that she was going to win.

The hunch as I see it, suggests that serendipitous episodes are more drawn out than a mere moment or flash of inspiration that Canon (1945) and others describe. The timing problem suggests serendipity is more procedural than an event; one might instead refer to a serendipitous phase, interlude or episode (Box 426:i1569).

Let us consider four situations where serendipity may be under- or over-stated. Firstly, scientific publication may omit all the messy dead-ends in research or work them into tidy narratives.[18] Peter Medawar took 'retrospective falsification', as termed by Barber and Fox, so far as to ask, somewhat sensationally, "Is the scientific paper a fraud?". Richard Feynman used his Nobel lecture, as several others have done, to describe the sequence of events and ideas in a way that he claimed he "cannot do elsewhere …in regular journals". Medawar and Feynman highlight how the standard format of an orthodox paper plays a role in suppressing much that is interesting in the scientific process for the serendipity researcher.

Secondly, observers of serendipity may be concerned with how meritorious their efforts will seem. The investigator may worry that if they acknowledge the role of serendipity, their accomplishments might be seen as mere accidents, with implications for their professional competence (or lack thereof).[19] The dispute between Waksman and his student over the discovery of streptomycin suggests that both felt entitled to claim credit but only the senior of the two disclosed serendipitous influences (Box 378:i1647; Meyers 2007:p157). Journal editors and referees might think descriptions of serendipity as mere digressions to be deleted.

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[18] Merton notes that "the elegance and parsimony prescribed for the presentation of the results of scientific work tend to falsify retrospectively the actual process by which the results were obtained" and "the etiquette governing the writing of scientific (or scholarly) papers requires them to be works of vast expurgation, stripping the complex events that culminated in the published reports of everything except their delimited cognitive substance. In short the audience demands a well-formulated argument that retrospectively imposes a logical form on the romance of investigation" (Merton and Barber 2004: 159 and 272).

[19] A serendipitous discovery may be seen as less worthy than one made without serendipity. As one Nobel laureate declared, "I think the Nobel Prize brought undue rewards. I got it for a purely accidental discovery. Anybody could have done that. This is often true in experimental physics. I think you can happen to be in a position where an important discovery is right there" (Merton and Barber 2004: 296).

Thirdly, a serendipitous discovery might have been noticed but not exploited because the observer was unable to convince others that the discovery was worth pursuing. Or perhaps the investigator is so committed to their search target by their patrons or future evaluators (e.g. Journal editors, referees, grant reviewers, technical directors), that they refuse to be distracted by new research goals. If we relax the assumption that the discovery is "happy" for everyone, and consider that the discovery might be "strategic" only for some, we might start asking for whom was the episode serendipitous. Consider for example an alcoholic who discovers his raffle ticket has won him a bottle of whiskey.

There are several examples of serendipitous observations not being recognised by others. In his masters dissertation, Scott reported his observation that an internal secretion from the pancreas controlled sugar metabolism. His supervisor dismissed the observation and edited the article before publication. Years later, the supervisor wrote to Scott, "I feel I personally have to shoulder a great deal of blame for discouraging you from going ahead with that work" (Sawyer 1966: 617). In another example, Marshall so struggled to convince gastroenterologists of his observation that bacteria could cause stomach ulcers that, in desperation, he resorted to self-experimentation (Meyers 2007:105).[20]

Fourthly, the unexpectedness of the discovery may not necessarily be the same as far as the researcher and the funder are concerned. Funders may have intended for there to be cross-over from their designated target, or investigators may have been well aware of multiple avenues that were potentially fruitful but disclosed only some of them. Such possibilities are difficult to discern beyond what is stated in proposals or funders' mission statements, but it is worth noting that proposals might be misleading for the purposes of tracing serendipity (because they reflect what the investigator thought would secure the funding, not what the investigator actually expected or planned to do) and mission statements can often be reduced to meaningless levels of generality. This may lead to over-estimates of serendipity.

These situations, where serendipity might be over- and under-stated, seem relevant to what Leahey calls "data editing". She shows large variation in how researchers deal with data, in how they clean datasets of apparently illogical, seemingly incorrect, or supposedly inaccurate

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[20] Fleming's discovery of lysozyme might have been received with more commotion had he not been such a monotonous and mumbling speaker (Meyers 2007:p63). In another example, the observer of viral transmission of cancer was derided, "Rous either has a hole in his filter or a hole in his head" (Kohn 1989:6).

data, and in researcher-opinions about 'proper' use of data. She finds that some of that variation depends on discipline, data collection method, characteristics of the data-editing situation like whether the problem is with an independent or dependent variable, and status and seniority (Leahey et al. 2003; Leahy 2004). It seems reasonable to think that research governance structures might broadly and systematically affect 'what's in and what's omitted', and have important implications for serendipity measurement (Owen-Smith 2001; Leahey 2008).

6. Conclusions

The main contribution of this paper has been to develop a typology of serendipity in research and to identify the main mechanisms through which it occurs. I drew on the Merton archives to help collect hundreds of examples of serendipity. Rather than explore their histories in pursuit of a research program in sociological semantics as Merton did, I analysed these examples for similarities and differences with respect to types and mechanisms of serendipity in order to clarify new empirical research questions in the field of research policy and explore their possible policy implications.

The typology took the notion of serendipity, widely but vaguely interpreted as simple happy accidents, and developed it into four, more specific, interpretations: Walpolian, Mertonian, Bushian and Stephanian. They are distinguished by firstly, whether there was a targeted line of enquiry when the discovery emerged, and secondly, what type of problem the discovery solved (see figure 1).

Four mechanisms of serendipity were explored. Serendipity may depend on the attributes of the observer and her situation (such as her perceptiveness, instruments and observation systems), or it may depend on the characteristics of the field of inquiry itself (such as when the growth of theory becomes conspicuous for discovery). I noted that errors took a prominent position in many accounts of serendipity, where seemingly critical substances have been dropped, spilled, inadvertently heated or exploded, forgotten about in pockets or drawers or laid to rest over holidays, contaminated, or subjected to methodological blunder and/or equipment malfunction. Serendipity may depend on such 'controlled sloppiness', where experimental design is loosely directed enough to allow discoveries to emerge, but not

so uncontrolled that variations cannot be traced back to a source. Lastly, I suggested that networks play dual, informational and teamwork, roles in serendipity, or conversely might discourage serendipity through groupthink effects.

The types help us to recognise some of the variety of serendipity that is possible, and allows us to appreciate that serendipity may exist in basic science, applied research and technological development activities. The mechanisms suggest that serendipity is not random, there may be important factors affecting its occurrence, and there may even be scope for altering its prevalence. Moreover, policy and theory implications may vary by type and mechanism of serendipity (see figure 3).

Serendipity does not necessarily strengthen rationales for untargeted research, and conversely do not necessarily weaken rationales for targeted research. The desirability of altering the prevalence of certain types of serendipity may depend on whether certain mechanisms of serendipity are believed to be associated with better research performance, or believed to be a hindrance to achieving targeted social goals.

The possibility of serendipity occurring through a variety of mechanisms should raise concerns among those seeking greater efficiency in research, and those framing innovation solely in terms of reducing uncertainty. The pursuit of efficiency could be supressing the error-borne serendipity mechanism, and driving out diversity in methodological approaches needed for Mertonian serendipity to come about. Greater pressure for efficiency might also make it harder to recognise and appreciate that it is possible for research to unexpectedly solve a later problem, where research may initially appear to have little utility and be deemed inefficient.

For those wishing to measure serendipity, I discussed some conceptual difficulties relating to the unit of analysis, and potential sources of over- and under-estimation of serendipity. There is clearly much about serendipity that currently defies large-sample quantitative analysis and will require qualitative efforts to go hand-in-hand for the time being.

Even while emphasising some of the measurement difficulties, I believe it is important to know more about the frequency, magnitude and qualitative nature of serendipity. Developing the implications of serendipity for policy and theory is not clear-cut, and will require a better sense of how serendipity is distributed across the research system. I hope that the typology of

serendipity and discussion of its mechanisms developed here facilitate research along these lines.

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