Scientific Creativity: Discovery and Invention as Combinatorial

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Universal thesis that scientific creativity entails a combinatorial process or procedure

- Introspective reports: e.g.,
  - Einstein (1945) “combinatory play … the essential feature in productive thought”
  - Poincaré (1921) “ideas rose in crowds; I felt them collide until pairs interlocked … making a stable combination”
- Psychological theories: e.g.,
  - Mednick (1962): “the creative thinking process as the forming of associative elements into new combinations which either meet specified requirements or are in some way useful. The more mutually remote the elements of the new combination, the more creative the process or solution” – hence the ubiquitous RAT
- AI/Computer simulations: e.g., evolutionary algorithms (D. Simon, 2013)
- Creative products: e.g.,
  - Thagard’s (2012) analysis of 100 discoveries and 100 inventions of the highest order

Here I hope to develop this thesis four ways

- *First*, I formalize the various types of combinations
  - Because not all combinations, nor even most, are creative
  - Because non-creative combinations may still lead to creative combinations
- *Second*, I specify the mandatory connection between combinatorial creativity and what has been variably styled “trial and error,” “generate and test,” “blind variation and selective retention,” etc.
- *Third*, I unify under a single specification *all* processes and/or procedures that generate potentially creative combinations
- *Fourth*, I work out the implications for distinct domains of creativity, especially the contrasts between the sciences and the arts

Two constraints on my treatment

- *One*, I focus on what’s going on within a single scientist's head, ignoring what also happens during lab meetings and other forms of group-level “brainstorming” (cognitive rather than social psychology)
- *Two*, I concentrate on problem solving, so that the interest largely concerns combinations that constitute solutions to problems regarding phenomena, such as
  - Identification: What is it?
  - Explanation: How does it work?
  - Prediction: What happens if?
  - Invention: By what device can this be done?

Formalization

- Given a particular problem, ideational or behavioral combinations are generated that represent potential solutions, as in
  - **Galileo Galilei** applying his artistic training in chiaroscuro to recognize that the dark and light patterns on the lunar surface represented mountains
  - **Isaac Newton** integrating Galilean mechanics with Keplerian astronomy to produce his gravitational account of the solar system
  - **Charles Darwin** realizing that Malthusian population growth would cause a “struggle for existence” that drives evolution via natural selection
  - **Thomas Edison** combining his telegraph and microphone inventions, thus converting the transcription of Morse code into the recording of sound
  - **James Watson** tinkering around with cardboard models of the four nucleobases to discover the DNA coding (AT and GC sans Chargaff’s rule)

Three combinatorial parameters: *p*, *u*, and *v*

- At the instant that problem solving starts, combinations may be described by the following three parameters (omitting subscripts):
  - p = the combination's *initial* probability or "response strength"
    - Where $0 \leq p \leq 1$ (e.g. not spontaneously generated during the initial session, to generated after a certain delay within the session, to instantaneously generated first)
  - u = the combination's *final* utility as a solution when fixed in the product
    - Where $0 \leq u \leq 1$ (e.g. completely useless, to merely satisficing, to satisfying all criteria)
  - v = the *prior* knowledge of the combination's final utility before generation
    - Where $0 \leq v \leq 1$ (e.g. utterly ignorant, to "educated guess," to "justified true belief")
- Hence, an eightfold combination typology (cf. Simonton, 2016, 2018; see also Tso, Ting, & Johnson, 2019, for quasi-Bayesian elaboration)

Eightfold combination typology
(where "→" = "nears value of")

- Two expertise-driven combinations ($v \to 1$; little knowledge gained):
    - $p \to 1$, $u \to 1$, $v \to 1$, i.e. "*explicit* expertise" (e.g., algorithmic solutions)
    - $p \to 0$, $u \to 0$, $v \to 1$, i.e. "*implicit* expertise" (viz. "ruled out of court")
- Two irrational combinations ($v \to 1$; acquired knowledge ignored)
    - $p \to 1$, $u \to 0$, $v \to 1$, i.e. "irrational perseveration" ("definition of insanity")
    - $p \to 0$, $u \to 1$, $v \to 1$, i.e. "irrational suppression" (e.g., extraneous bias)
- Four "blind" combinations ($v \to 0$; so new knowledge acquired)
    - $p \to 1$, $u \to 1$, $v \to 0$, e.g. "lucky guess" or "right for the wrong reason"
    - $p \to 1$, $u \to 0$, $v \to 0$, e.g. "problem finding" – and thereby future creativity
    - $p \to 0$, $u \to 0$, $v \to 0$, e.g. "mind wandering" or "tinkering" – which can lead to
    - $p \to 0$, $u \to 1$, $v \to 0$, viz. "creative" idea or response … accordingly …

Formal three-criterion creativity definition

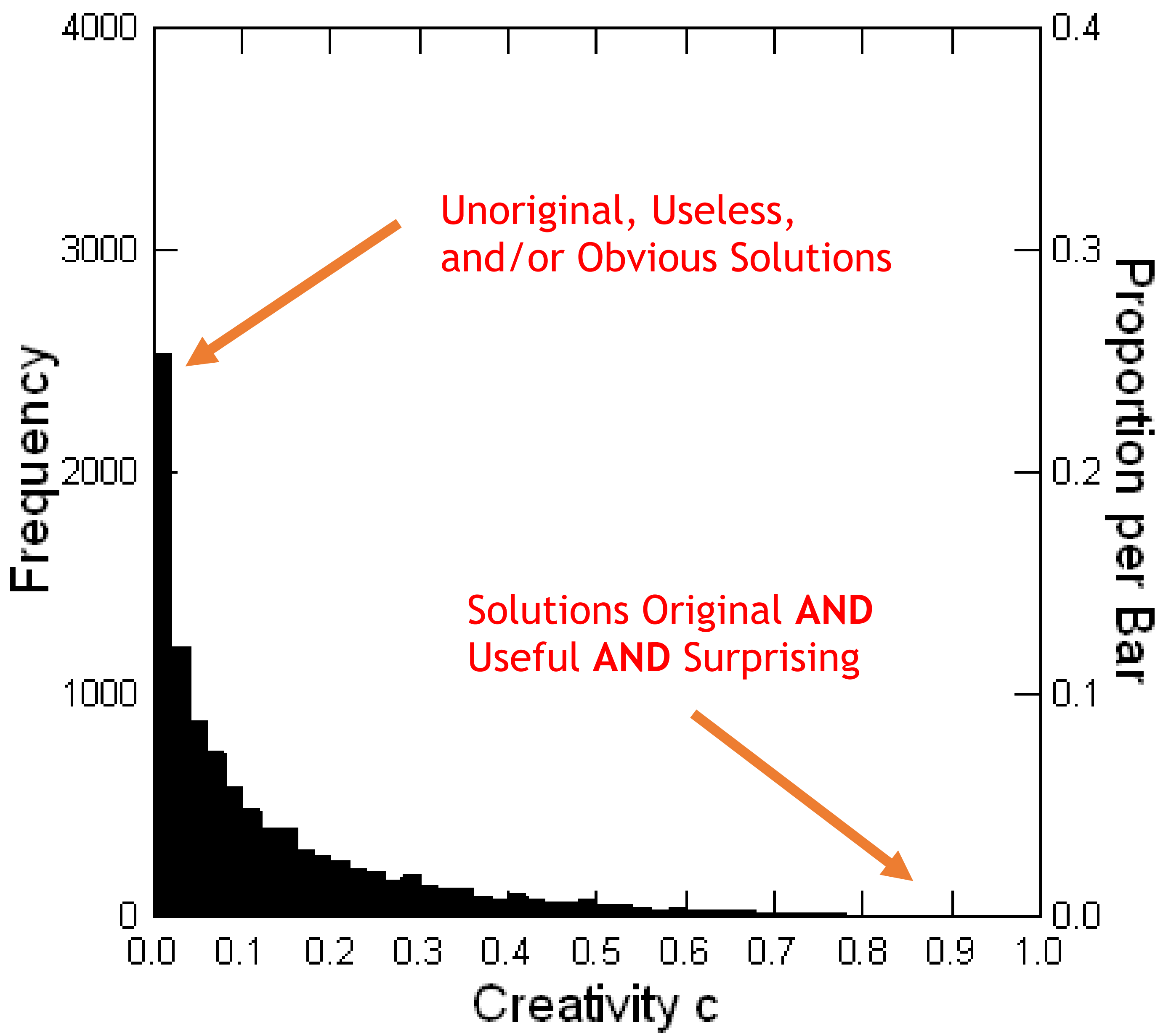
- Let $(1 - p)$ = *originality* and $(1 - v)$ = *surprise* (new knowledge gained),
- then let a combination’s *personal creativity*
- **$c = (1 - p)u(1 - v)$**, the joint product of originality, utility, and surprise
  - cf. Boden (2004): novel, valuable, and surprising (in her *P*-creativity)
  - cf. US Patent Office: new, useful, and nonobvious (“ordinary skill in the art”)
  - cf. Amabile (1996): novel, appropriate (useful, correct, or valuable), and task heuristic rather than algorithmic (i.e., $v \to 0$ rather than $v \to 1$, respectively)
- Three points:
  - The “standard definition,” which omits the third criterion v, absolutely illogical
  - Indeed, without v, *explicit expertise* is indistinguishable from a *lucky guess*!
  - In short, the prior knowledge brought into the initial situation must be considered!😫
- This formal definition then has six implications

The definition's six implications

- *First*, personal creativity is a continuous variable ($0 \leq c \leq 1$)
  - e.g., moderate creativity: p = .2, u = .8, and v = .5, which yields c = .32
- *Second*, whenever $c << 1$, creativity of a solution may represent an infinitely varied mixture of values for originality, utility, and surprise
  - Yet the *qualitative* character of the creative solution will differ depending on which of the three criteria dominates (e.g., applied vs. pure research)
- *Third*, given multiplicative rather than additive integration, each criterion becomes *necessary but not sufficient* for personal creativity
  - i.e., if any factor equals zero, then their product equals zero
  - e.g. perpetual motion machine of 1st or 2nd kind (p = .1, u = 0, v = 1 and c = 0)

The definition's six implications

- *Fourth*, whenever $u > 0$ and $v < 1$, then c maximizes when $p = 0$
  - Therefore, although an incubation period is *not* required to generate creative solutions, those solutions that require incubation because the initial probability is zero will tend to be more personally creative
    - e.g. Wallas's (1926) four stages of preparation, **incubation**, illumination, and verification (based on the experiences of superlative scientists, such as Helmholtz)
  - Yet, creativity largely uncorrelated with incubation's temporal duration because the latter contingent on chance external stimuli and internal associations (cf. "constrained stochasticity" in Carruthers, 2018; Simonton, 2003)
    - e.g. Archimedes's famous eureka experience would not have produced a more creative solution to the gold crown problem had he delayed taking a bath a day or more
- *Fifth*, given multiplicative rather than additive integration, creative solutions are necessarily far more rare than noncreative solutions
  - e.g., a simple Monte Carlo simulation in which values of the three parameters are randomly generated (cf. implications of central limit theorem)



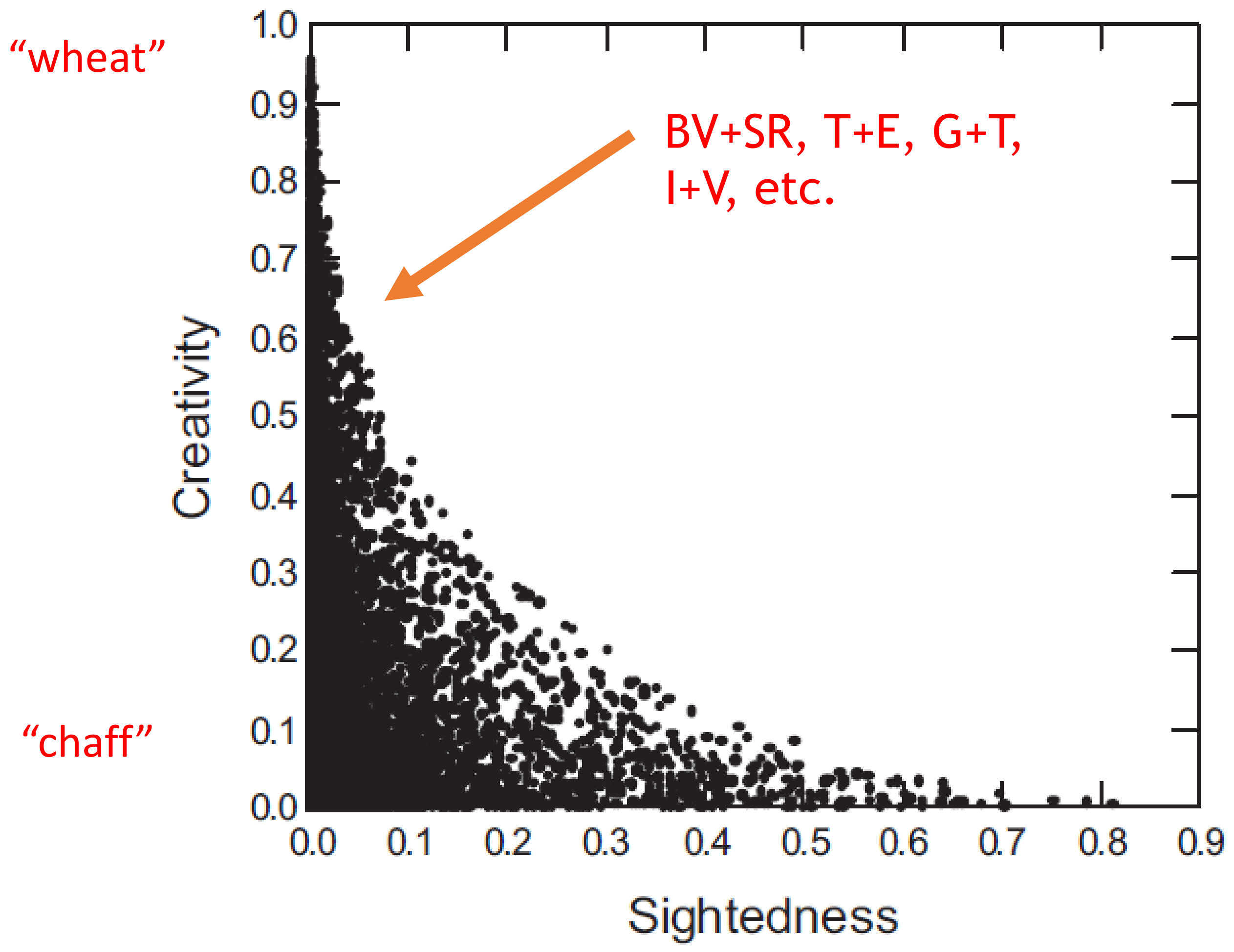
Unoriginal, Useless, and/or Obvious Solutions
Solutions Original AND Useful AND Surprising
Frequency
Proportion per Bar
Creativity c
4000
3000
2000
1000
0
0.4
0.3
0.2
0.1
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

The definition’s six implications

- *Sixth*, and last, because the solution utilities for creative combinations are unknown or incompletely known in advance of the generation of the potential solutions (i.e., $v << 1$), then those solutions must undergo a second step of directed evaluation or assessment
  - The two steps have been variously styled:
    - **trial and error** (T+E; Bain, 1855),
    - **illumination and verification** (I+V; Wallas, 1926),
    - **generate and test** (G+T; various AI algorithms),
    - **conjecture and refutation** (C+R; Popper, 1963), and
    - **blind variation and selective retention** (BV+SR; Campbell, 1960)
    - “spontaneous behavior” plus **selection by consequences** (SB+SC?; Skinner, 1981)
  - 2nd step either external (Skinnerian) or internal (Popperian)(Dennett, 1995)

The definition's six implications

- *Sixth*, and last, because the solution utilities for creative combinations are unknown or incompletely known in advance of the generation of the potential solutions (i.e., $v \ll 1$), then those solutions must undergo a second step of directed evaluation or assessment
  - To illustrate, let us define a potential solution attribute called "sightedness" using the three parameters, namely, $s = puv$, where $s = 1$ when $p = u = v = 1$ (yielding an index of explicit expertise)
    - Then another simple Monte Carlo simulation yields the following scattergram:



Albert Einstein "If we knew what we were doing, we wouldn't call it research" and "Most of my intellectual offspring end up very young in the graveyard of disappointed hopes"

But where do the potential combinatorial solutions originate in the first place?

- Answer: Whatever works! (cf. “anything goes” Feyerabend, 1975)
- Researchers have proposed an impressive number of combinatorial generators that can feed potential solutions into the selection hopper
- e.g., remote association, divergent thinking, cognitive disinhibition (defocused attention), primary (primordial) process (“regression in the service of the ego”), dreams, psychoactive drugs, organic brain disorders, synesthesia, intuition, overinclusive (allusive) cognition, mind wandering, analogy, conceptual reframing (frame shifting), broadening perspective, juggling induction and deduction, problem dissection, reversal, tinkering, play, heuristic and systematic searches, serendipity, Geneplore, Janusian, Homospatial, and Sep-Con Articulation thinking
- Yet there’s **No Free Lunch**! *All* work *some* of the time, *none* works *all* of the time - and there’s no telling beforehand *which* will work best!

But where do the potential combinatorial solutions originate in the first place?

- Even so, each and every generator shares one key characteristic:
    - the capacity to generate low probability potential solutions with unknown or incompletely known utility values
    - i.e., $p \to 0$ and $v \to 0$ while $0 \leq u \leq 1$
    - The latter ignorance then requires a utility evaluation or test
- Even in highly inspired "Eureka!" moments, acceptable utility is by no means guaranteed:
    - Hence, Wallas justified in adding the verification stage after the illumination stage to accommodate "Oh, shucks!" events
    - Such a requirement increases with the complexity of the utility criteria (e.g., what counts as a complete explanatory model of DNA's molecular structure?)

But where do the potential combinatorial solutions originate in the first place?

- Two phenomena illustrate the exceptional circumstances under which highly creative ideas are often generated in the sciences:
  - Internal circumstance: **Mind wandering** (Gable, Hopper, & Schooler, 2019).
    - "The bath, the bed, and the bus" (Boden, 2004, p. 25)
    - Because $p \to 0$ and $v \to 0$, then $0 \leq u \leq 1$
    - Hence, a creative combination can be spontaneously generated when engaged in some mundane or semi-alert activity, like taking a bath, waking up in bed, or boarding a bus
  - External circumstance: **Serendipity** (Cannon, 1940; Mach, 1896)
    - Classic examples: penicillin, electromagnetism, X-rays, phonograph, ozone, etc.
    - Note the unique parameter values: $p = v = 0$ *exactly*, but $u \to 1$
      - i.e., the highly useful combination could be neither spontaneously generated nor anticipated
    - Q: But what of Pasteur's "Chance favors the prepared mind"?
      - A: Scientists must have the expertise to evaluate the originality, utility, and surprise

How does scientific creativity differ from artistic creativity?

- Combinatorial processes and procedures permeate all forms of creativity, including in the arts
  - The latter is evident from multiple sources, such as introspective reports, theoretical models, computer simulations, single-case studies, etc.
- Yet fundamental contrasts distinguish scientific and artistic creativity
- The most obvious contrast is that the ideas undergoing combination are sampled from distinct domains (e.g., Einstein versus Picasso)
  - Including whether those domains are closed or open to extra-domain ideas
- Beyond those inevitable differences, contrasts can be conjectured based on the creativity definition alone

How does scientific creativity differ from artistic creativity?

- First, scientific *combinations*
  - Utility u more precisely delineated (e.g., no “poetic license” allowed)
  - Prior knowledge value v more often higher (i.e., expertise-driven hunches)
  - Initial probability p more likely higher (viz., pure originality less valued)
- Second, scientific *products*
  - Larger proportion of the combinations collated into such products represent explicit scientific expertise rather than creativity (i.e., $s = puv = 1$)
    - lit reviews, methods and statistics boilerplate, routine citations, standard format, etc.
- Third, scientific *consensus*
  - Personally assessed “little-c” creativity more strongly corresponds to consensually assessed “Big-C” creativity [i.e. $c = (1 - p)u(1 - v) \approx C = f(P, U, V)$]

Questions?

e.g., Like, what about the “combinatorial explosion”?