# The invention of the transistor: revisiting the « *magic month* » through the prism of C/K design theory

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11th SIG Design theory, ENSMP, Paris.

## Why the transistor ?

- December 16th, 1947 : demonstration of a working point-contact « transistor » at Bell Labs by J. Bardeen & W. Brattain
  - A technical breakthrough
  - Leading to « Junction transistor » (1948) …and others !
  - Opening the « Silicon Valley » and the « Information age »
- A scientific breakthrough : 1956 Nobel Prize in Physics for W. Shockley, J. Bardeen & W. Brattain.

- A very rich empirical material :
  - L. Hoddeson research program on the transistor (1981 – 1997)
  - W. Shockley reflection on the process (Shockley, 1974 & 1976)

## The *« magic month »* (Shockley, 1974)

- A term coined by Shockley
- a « **burst of creativity** » at Bell Labs culminating with the Point-Contact transistor

**But :**

- Even in the paper : more than a month
- **Two different designs**
  - point-contact

    and
  - junction transistor (feb. 1948)

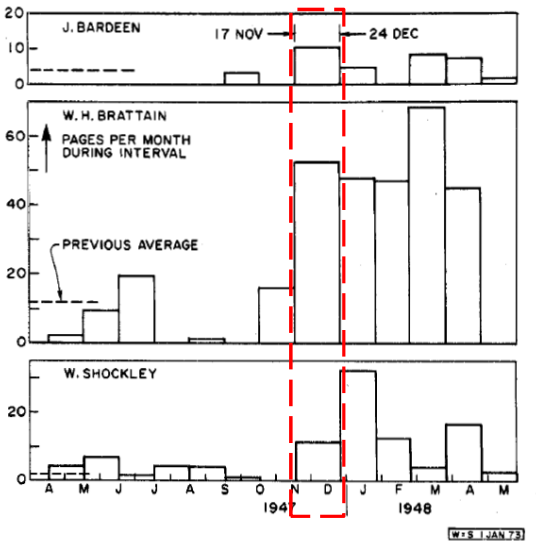


Fig. 3. The quantitative impact of the observation of 17 November 1947 on "the will to think" as shown by the number of notebook pages used per month. (Areas represent total pages used and ordinates represent rates. Each bar is one calendar month except for the one starting on 17 November 1947 which is lengthened to Christmas Eve 1947 to include the famous notebook entry of Walter H. Brattain reproduced in Fig. 17. After 25 April 1948, Brattain shared notebook use with an increased number of technical assistants; since the data then were not comparable to earlier data, they have been omitted.)

## The *« magic month »* (Shockley, 1974)

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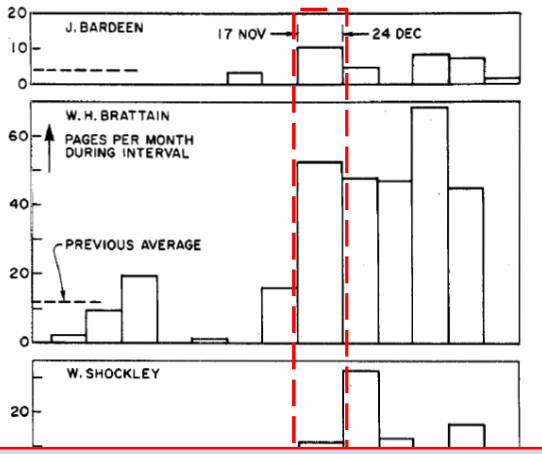



How did they get to this revolution ?

⇒ **revisit the *magic month* through the prism of CK design theory** (Hatchuel & Weil, 2009) to understand the story and the design process behind the transistor

⇒ **emphasize the role of organization and time (long-term history) in the process**

## The starting point : replacing vacuum tubes

- A research topic at Bell Labs supported by M. Kelly's vision in the mid-30's : *replacing vacuum tubes (VT) function to function by a « semi-conductor amplifier ».*
  - Well known weaknesses of VT: heating, power hungry, fragile, size…
- Initial approach : adapt the components of VT into semiconductor material (*structure to structure*)
  - Semiconductors = potential candidates to replace VT
  - 1st "naïve" concept : looking for a "semiconductor triode", trying to insert a "grid" in a metal / semiconductor device (or two layers of semiconductor) = failure

## K-base ($K_0$) – 1945

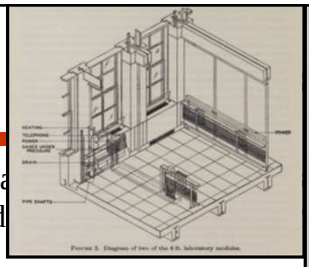
- A "rough" theoretical basis :
  - quantum theory of rectification (Mott-Shottky theory – for copper oxyde / concept of "majority carrier")
  - quantum theory of metals / conduction
- W. Shockley (at Bell Labs since1936) experiments on a semiconductor amplifier :
  - Structure to structure experiments (Brattain & al.) => failure
  - a "field-effect" amplifier in 1939 and april 1945 => only failures
- War Research effort on radar (rectification for radar)
  - new K on the metallurgy of SC in particular Silicon (Si) and Germanium (Ge)
  - Identification of « p-n junction » in Si.

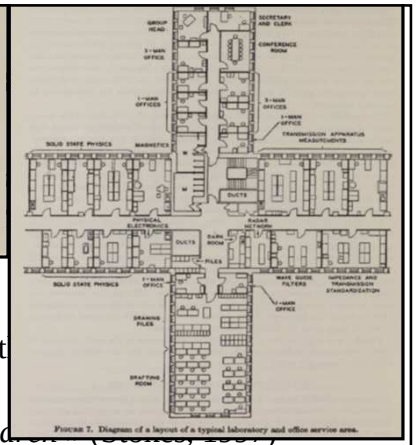
## The organization

- June 1945 : creation of the Solid States Physics Department at Murray Hill led by W. Shockley & S. Morgan

- An original research strategy
  - A multidisciplinary approach directly inherited from WWII Rad Lab project
  - A case of « *use-inspired basic research* » (Stokes, 1997)
  - A very careful design of the physical environment to enhance communication between the actors involved

- Octobre 1945 : J. Bardeen's arrival at Bell Labs
  => 1st breakthrough in K





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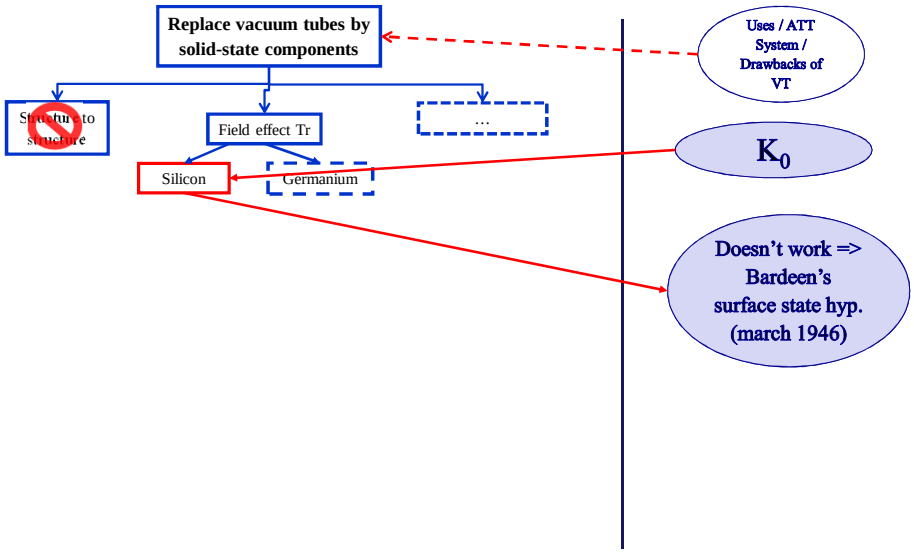
« It is frequently said that having a more-or-less specific practical goal in mind will degrade the quality of research. I do not believe that this is necessarily the case and to make my point in this lecture I have chosen my examples of the new physics of semiconductors from research projects which were very definitely motivated by practical considerations. » (W. Shockley Nobel Lecture, 1956).

=> « *Respect for scientific aspects of practical problems* » (1974)

## Bardeen's *surface state* hypothesis

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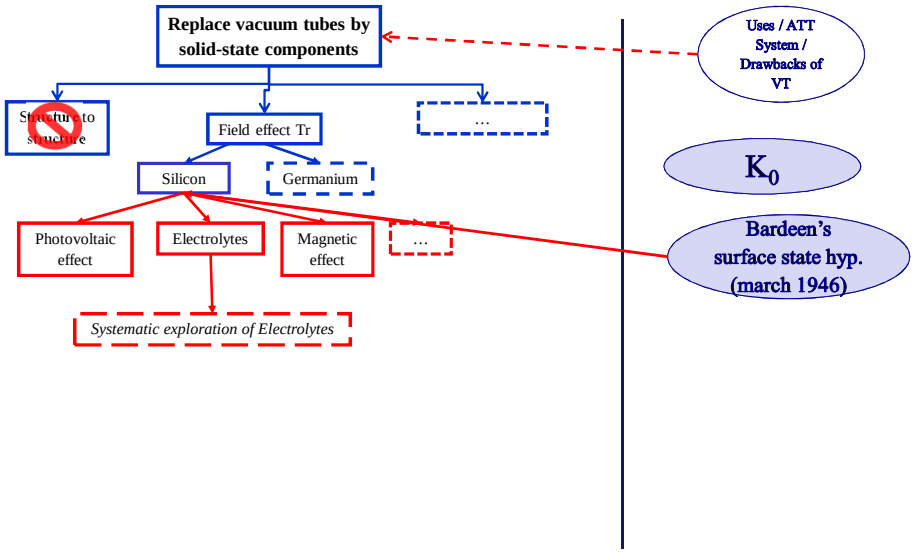
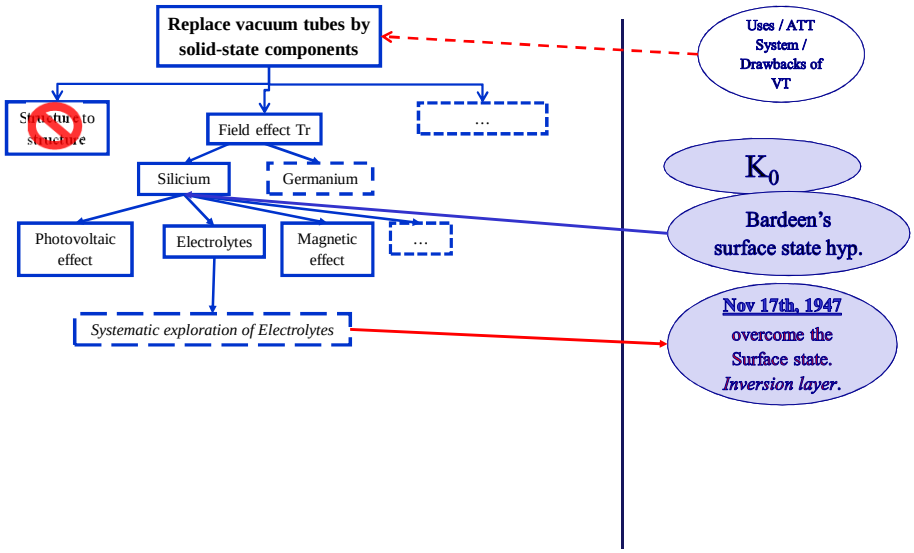


## The *magic month* (17 nov. - 16 dec. 1947)

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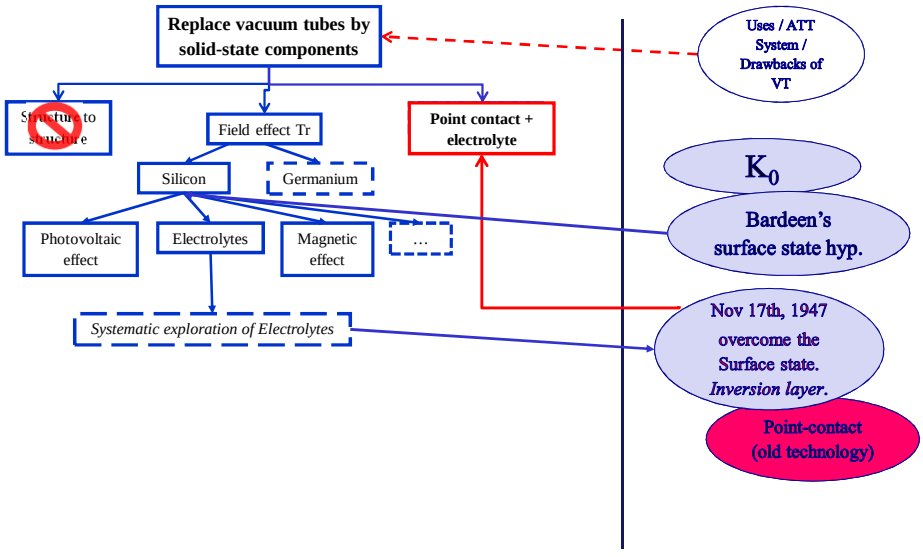

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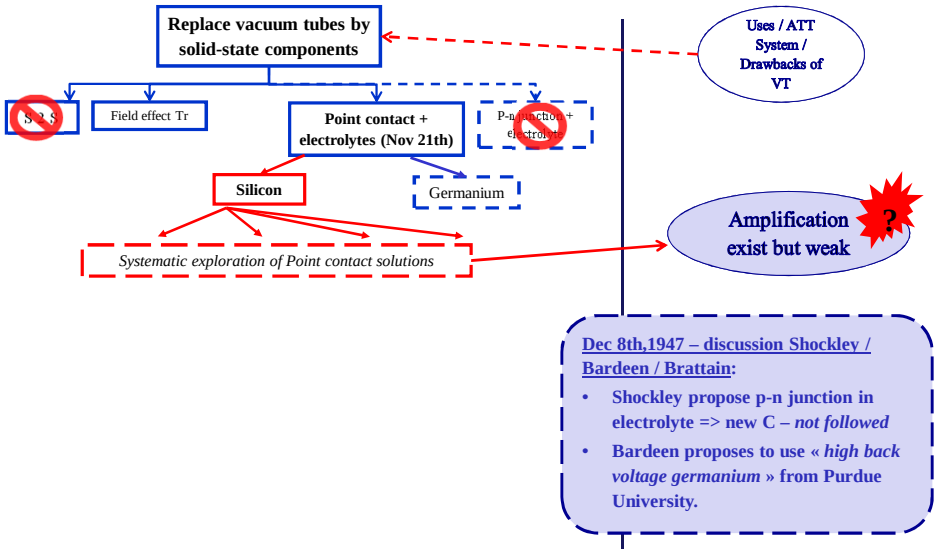


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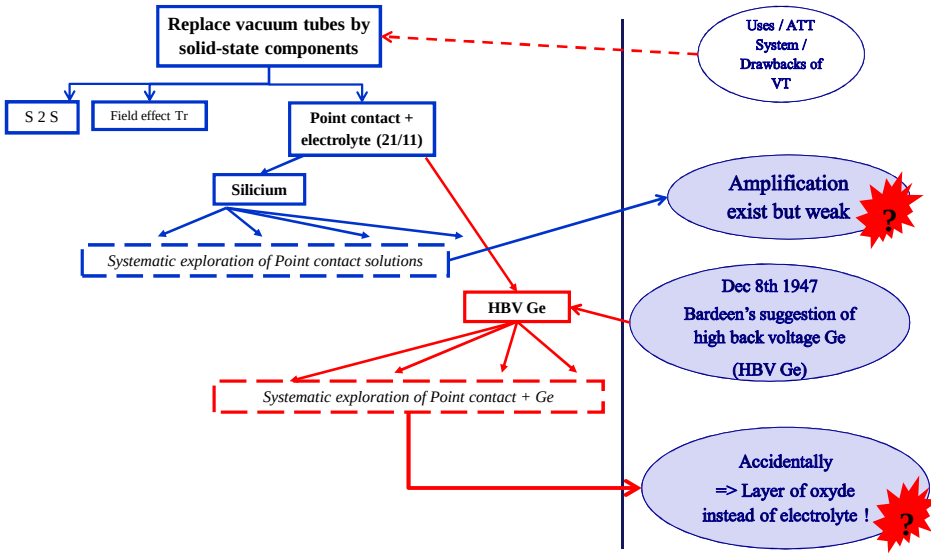

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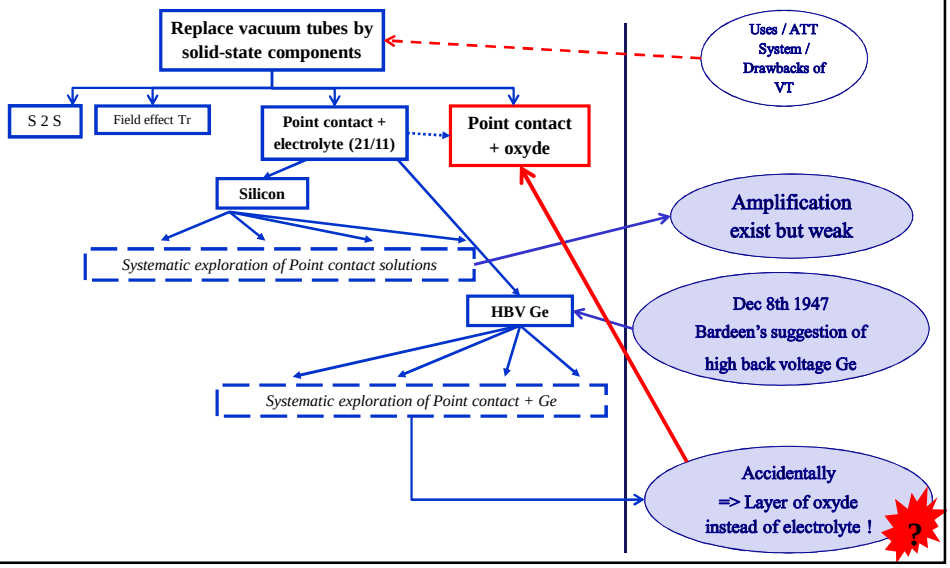


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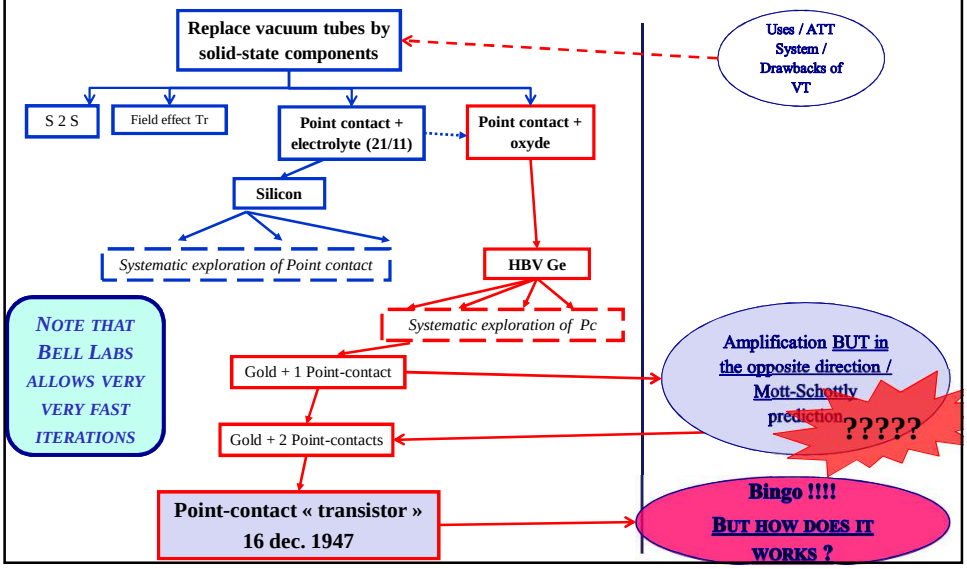


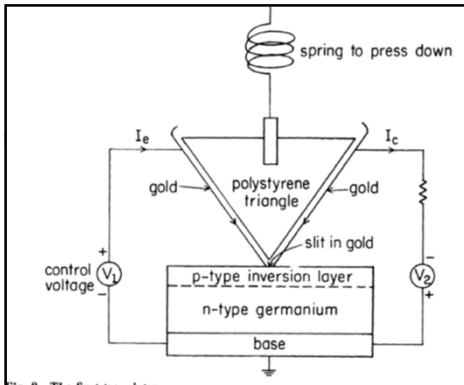
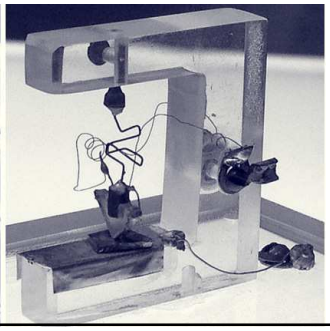


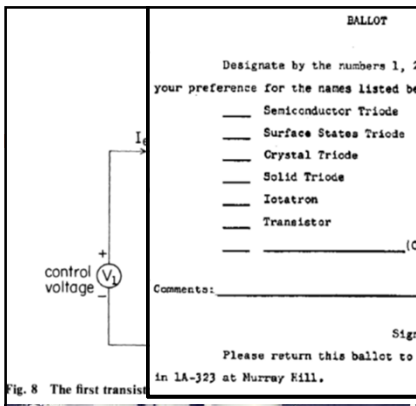

Fig. 8 The first transistor.

## The « point-contact transistor »

**(dec. 16, 1947)**

**Named « transistor » in may 1948**

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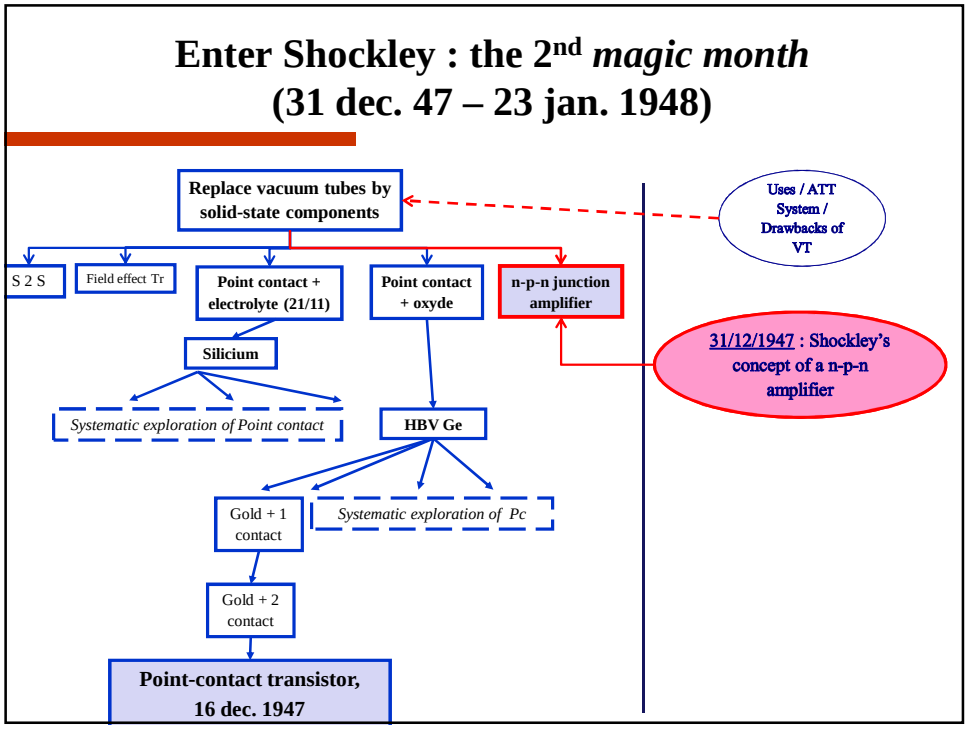
## The « point-contact transistor »

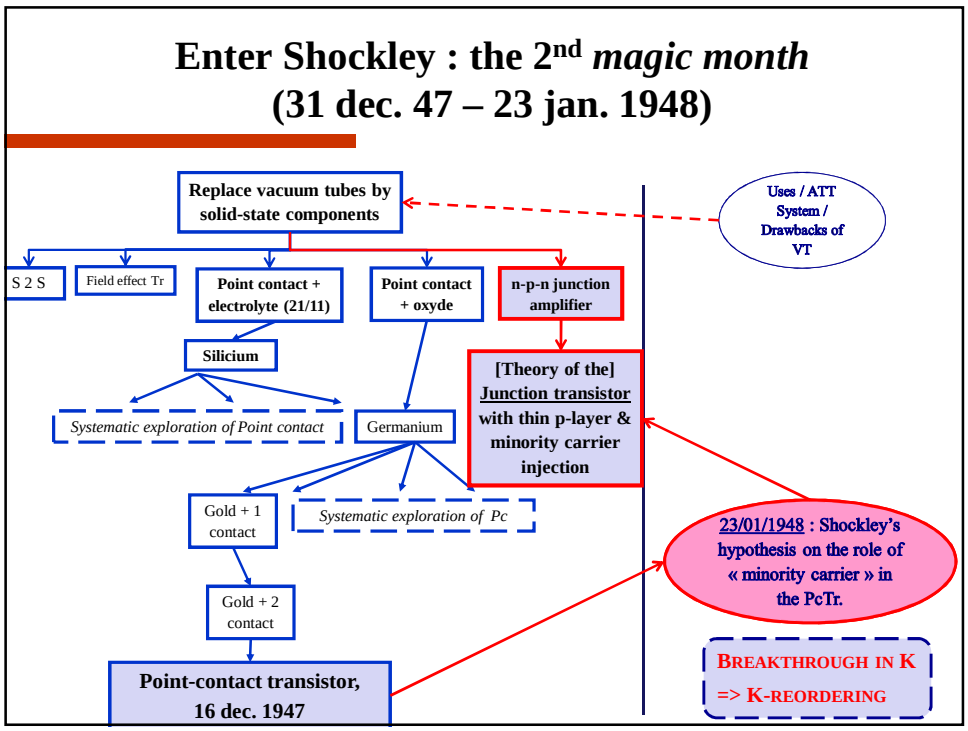
**(dec. 16, 1947)**

**med « transistor » in may 1948**

« *Frankly Bardeens and Brattain's point-contact transistor provoked conflicting emotions in me. My elation with the group's success was balanced by not being one of the inventors.* »

W. Shockley, 1974, p. 54.


Enter Shockley : the 2nd magic month
(31 dec. 47 – 23 jan. 1948)
Replace vacuum tubes by solid-state components
Uses / ATT System / Drawbacks of VT
S 2 S
Field effect Tr
Point contact + electrolyte (21/11)
Point contact + oxyde
n-p-n junction amplifier
Silicium
31/12/1947 : Shockley's concept of a n-p-n amplifier
Systematic exploration of Point contact
HBV Ge
Gold + 1 contact
Systematic exploration of Pc
Gold + 2 contact
Point-contact transistor, 16 dec. 1947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[Theory of the] Junction transistor with thin p-layer & minority carrier injection
Systematic exploration of Point contact
Germanium
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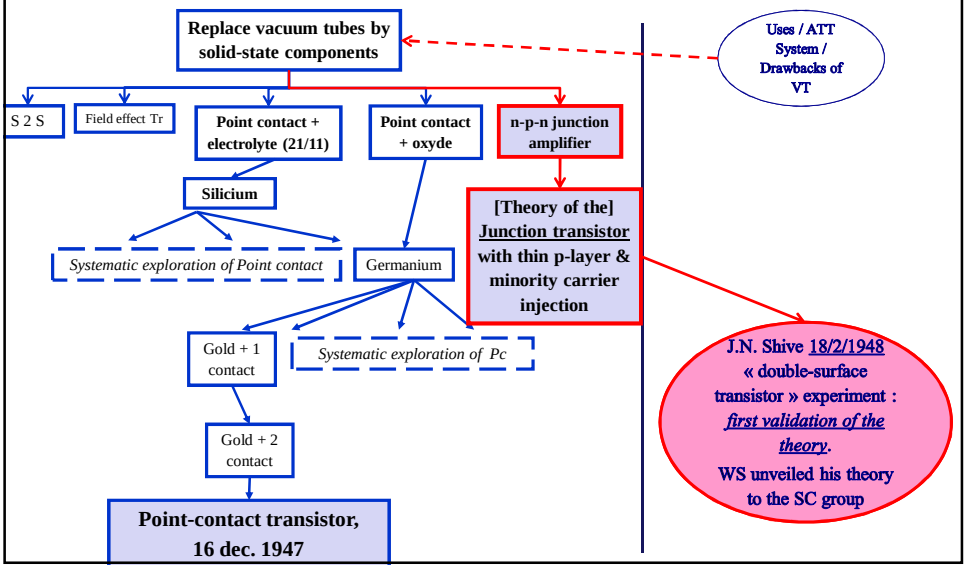
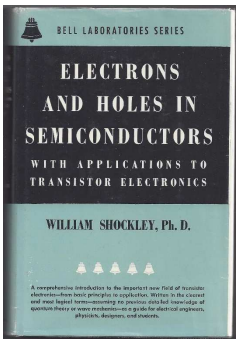
Systematic exploration of Pc
23/01/1948 : Shockley's hypothesis on the role of « minority carrier » in the PcTr.
Gold + 2 contact
BREAKTHROUGH IN K => K-REORDERING
Point-contact transistor, 16 dec. 1947

# Enter Shockley : the 2nd *magic month* (31 dec. 47 – 23 jan. 1948)




# Designing the transistors




- **Point contact transistor :**
  - A breakthrough without a theoretical understanding
  - Far from « structure to structure » replacement of VT
  - Creation of an exploratory development group
  - An industrial nightmare !!!

- **Junction transistor**
  - Start as a purely theoretical device
  - 2 years of R&D : working April, 12, 1950 / Announced summer, 1951.
    - In particular on the metallurgy of germanium : « *good p-n junction prepared by sparks & teal by changing the doping of the melt in germanium crystal grower by « pill dropping » and subsequent double doping to make n-p-n structures* » (in Shockley, 1976)
  - Publication of Shockley's classic *Electron and holes in semiconductors with application to transistor electronics* (nov. 1950) => Complete re-ordering of the K-base ~ bible of the Silicon Valley

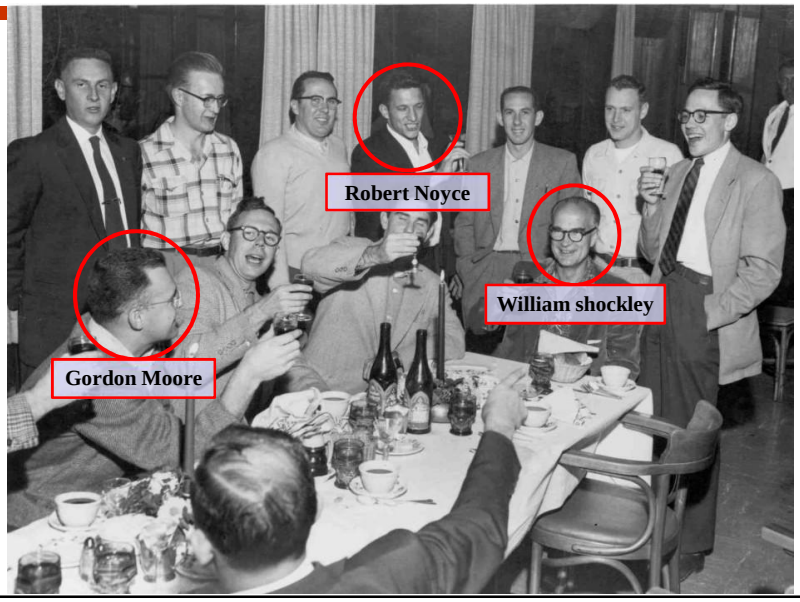
## Epilogue (1)

- Shockley leaves Bell Labs in 1955 to create *Shockley Semiconductor Laboratory => roots of the* Silicon Valley

- The Junction Transistor will not « replace » vacuum tubes before years.
  - 1st important application = Minuteman ICBM
  - Portable radios / hearing aids…
  - and, in the late 1950s : computers
    - => Essentially : miniature device + new uses !!
    - => Neither « structure to structure » nor « function to function »

- Nobel Prize in physics for SBB in 1956.

## Nobel celebration at Shockley Lab, 1956



## Epilogue (2)

- The *magic month* is only the tip of the iceberg
- Unveiled the creation process of a new K-base and the ensuing massive K-reordering (Hatchuel & al., 2015; Le Masson & al., 2017)
  - New theoretical basis : quantum physics
  - A ten years long process (including WWII)
  - Supported by M. Kelly's initial vision…
  - … and Bell Labs multi-disciplinary approach to research.
  - A complex process interlacing theoretical hypothesis, experimentation, working-but-why devices, calculations, insights and creative discussions between high-level scientists.
- New K-base proved to be extremely generative : incredible expansion in C and birth of the information age / Silicon Valley

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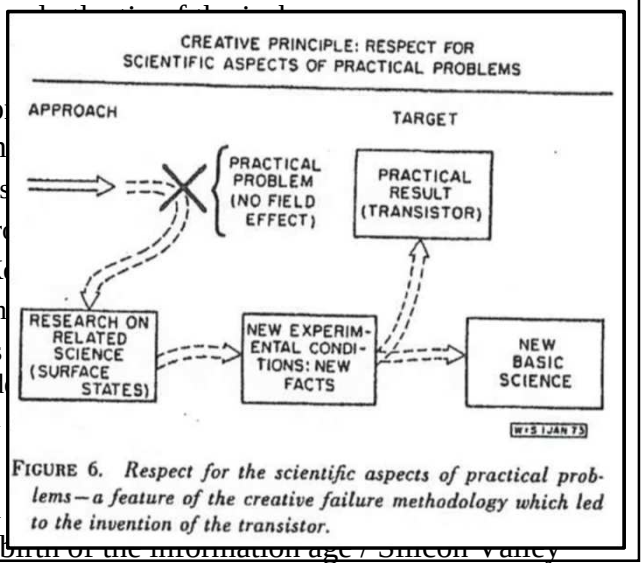
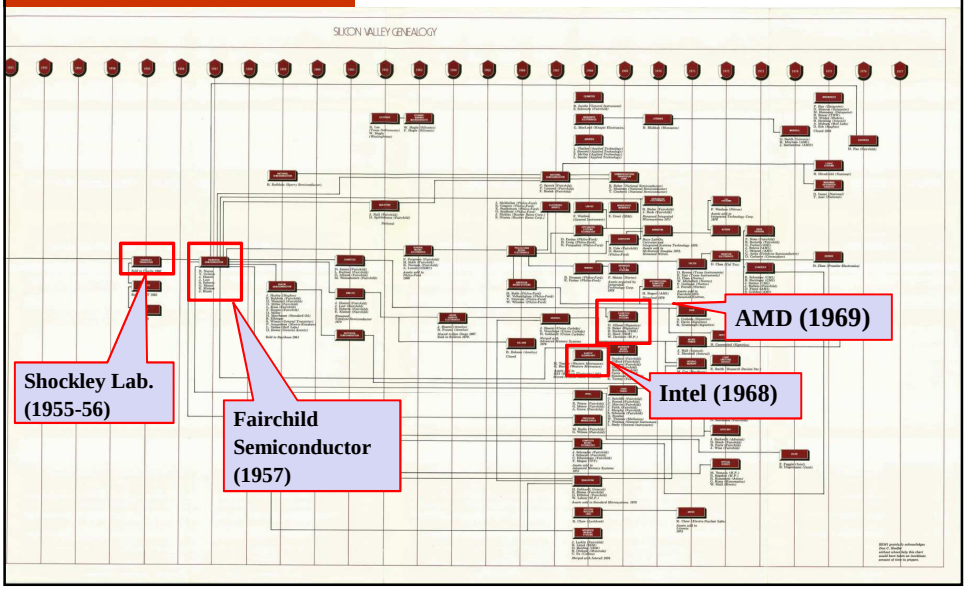



FIGURE 6. *Respect for the scientific aspects of practical problems—a feature of the creative failure methodology which led to the invention of the transistor.*

## Shockley Lab
## and the growth of the Silicon Valley





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