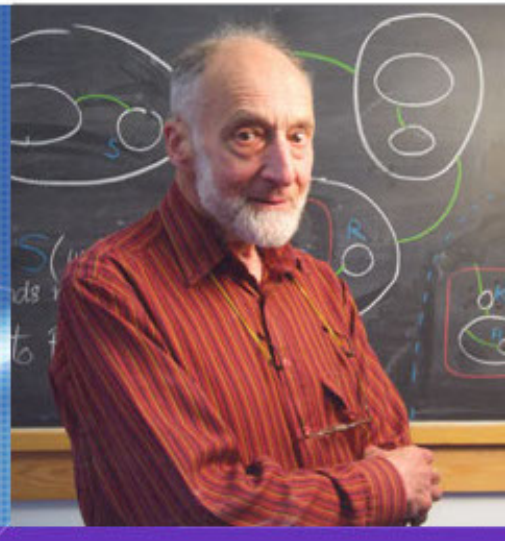
Alcatel·Lucent

Robin Milner, 1934-2010

Concurrency: interaction, bisimulation, naming

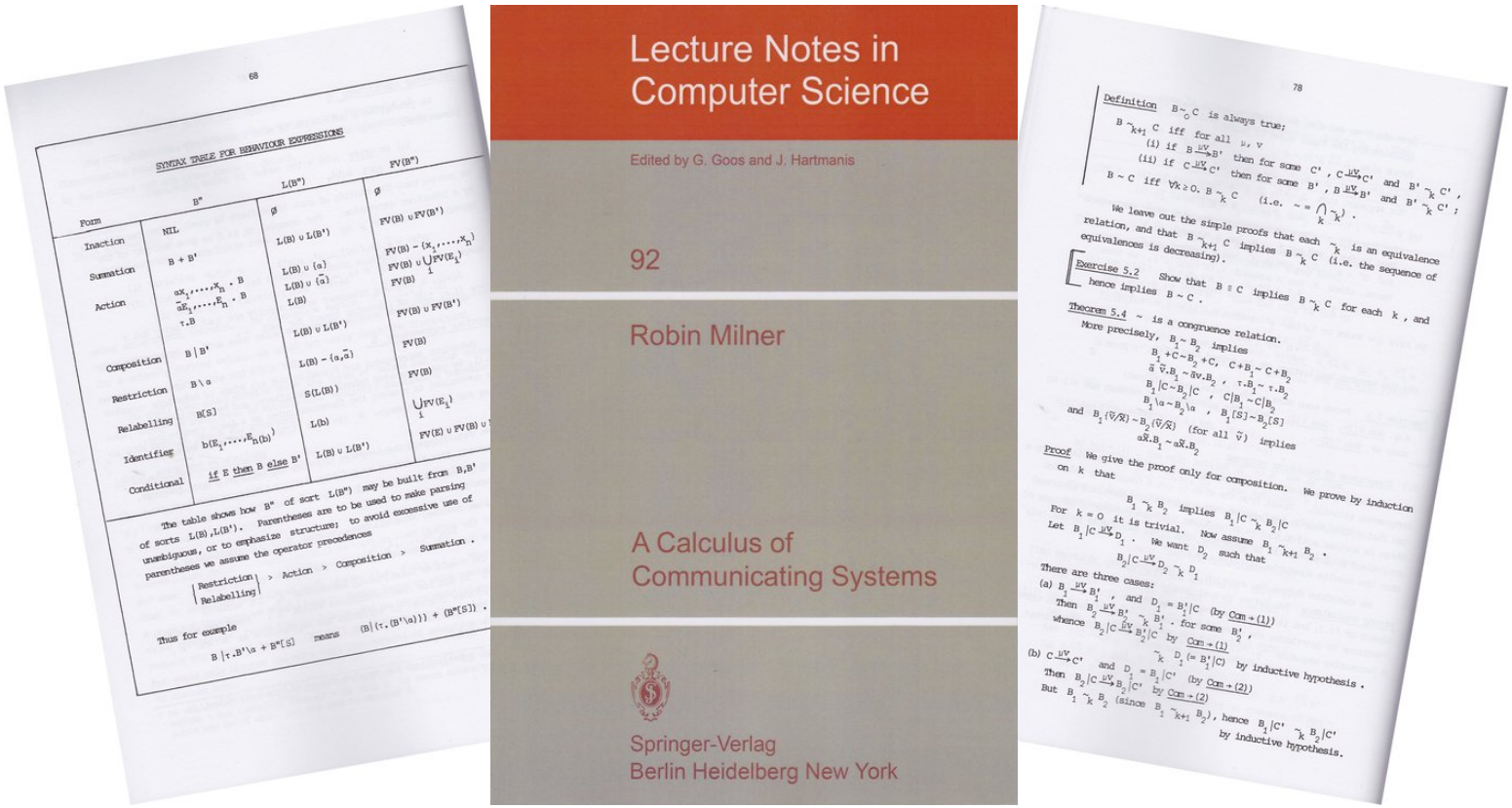


Alan Jeffrey

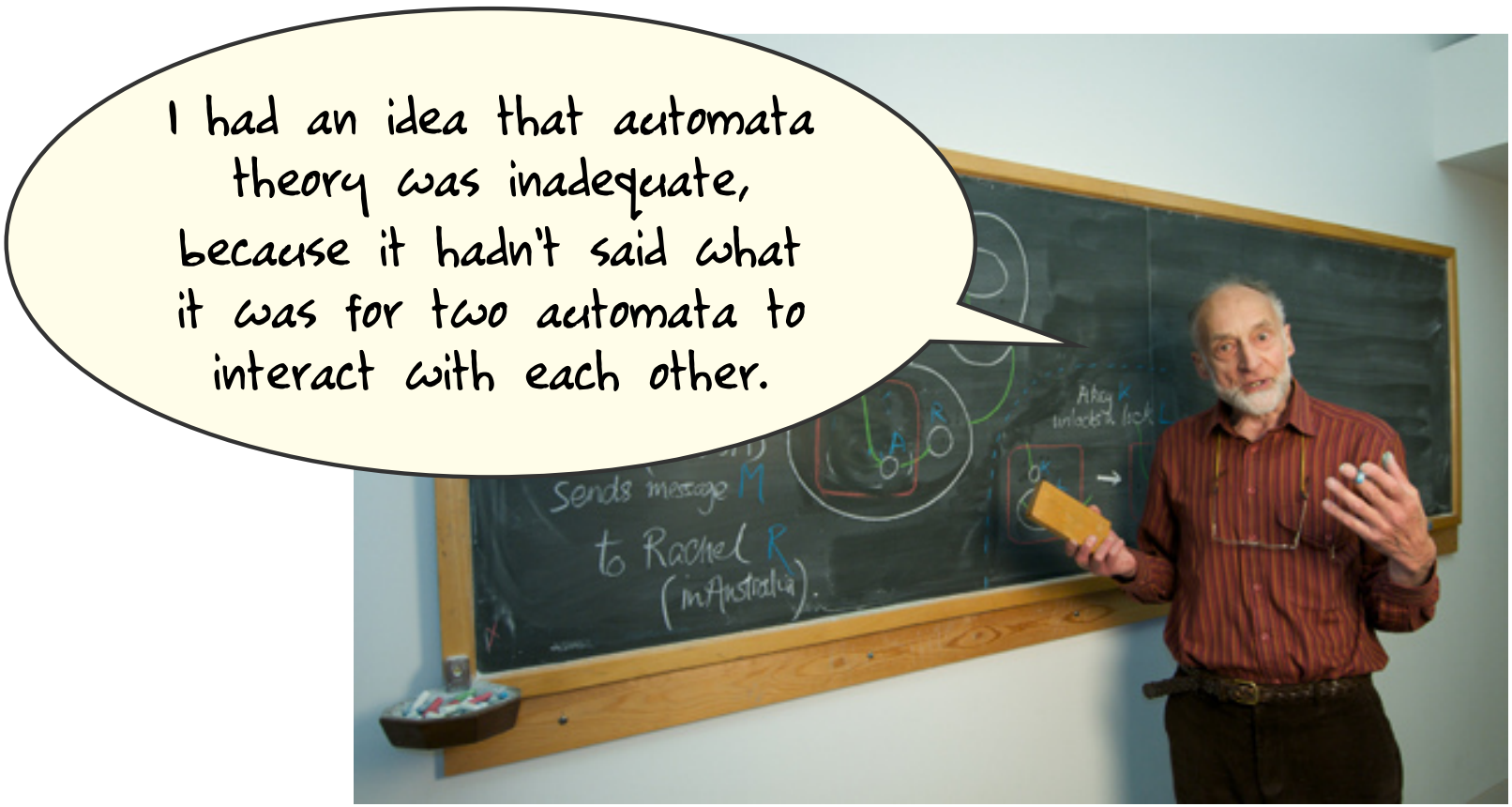
Bell Labs, Enabling Computing Technologies Research

January 2011, ACM Principles of Programming Languages

Interaction



Concurrency = automata + interaction



All quotes from Martin Berger's An Interview With Robin Milner, 2003.

A Calculus of Communicating Systems

- Existing and simultaneous work on communication and processes.
  - Petri Nets (1962).
  - Dijkstra (1968) Cooperating Sequential Processes.
  - Owicki-Gries (1976) Hoare logic for parallel programs.
  - Lamport (1978) partially ordered events.
  - Pnueli (1979) temporal logic.
  - Hoare (1979) Communicating Sequential Processes.
  - Hennessy and Plotkin (1979) resumptions.
  - . . .

A Calculus of Communicating Systems

- Existing and simultaneous work on communication and processes.
- Labelled transition systems.
  - Automata where every state is an acceptor.
  - Alphabet of actions ℓ, coactions $\bar{\ell}$ and τ.
  - Support *interaction*:

$$\frac{P \xrightarrow{\ell} P' \quad Q \xrightarrow{\bar{\ell}} Q'}{P \mid Q \xrightarrow{\tau} P' \mid Q'}$$

A Calculus of Communicating Systems

- Existing and simultaneous work on communication and processes.
- Labelled transition systems.
- Process language.
  - Small, inductively defined syntax with recursive processes.
  - Inspired by language of regular expressions; includes interaction.
  - Semantics given operationally (cf. Plotkin) as an LTS.

A Calculus of Communicating Systems

- Existing and simultaneous work on communication and processes.
- Labelled transition systems.
- Process language.
- Inductively defined equivalence of processes.
  - $P \sim_0 Q$.
  - $P \sim_{n+1} Q$ whenever, for all α:
    - If $P \xrightarrow{\alpha} P'$ then, for some Q', $Q \xrightarrow{\alpha} Q'$ and $P' \sim_n Q'$.
    - If $Q \xrightarrow{\alpha} Q'$ then, for some P', $P \xrightarrow{\alpha} P'$ and $P' \sim_n Q'$.
  - $P \sim_\omega Q$ whenever, for all n, $P \sim_n Q$.

  Now called stratified bisimulation.

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  - $P \sim_\omega Q$ whenever, for all n, $P \sim_n Q$.

  Now called stratified bisimulation. Implicit in earlier work:
  - Moore's algorithm for DFA minimization (1956).
  - Proof of Myhill-Nerode Theorem (1958).

  But now a first-class citizen, not a proof or algorithm technicality.

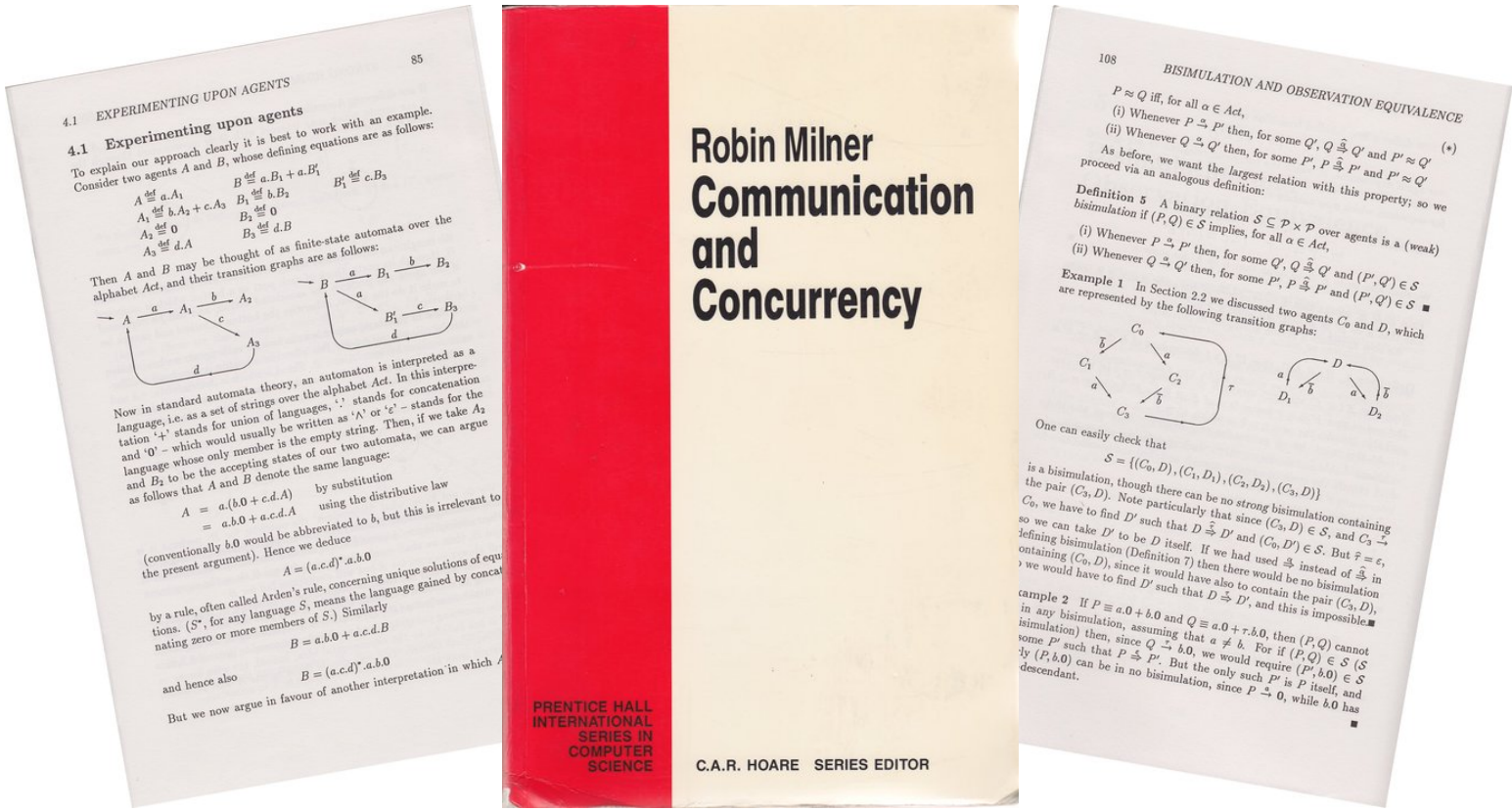
A Calculus of Communicating Systems

- Existing and simultaneous work on communication and processes.
- Labelled transition systems.
- Process language.
- Inductively defined equivalence of processes.
- Results.
  - Stratified bisimulation is a congruence.
  - Sound and complete axiomatization.
  - Logical characterization (Hennessy-Milner logic).

A Calculus of Communicating Systems

- Existing and simultaneous work on communication and processes.
- Labelled transition systems.
- Process language.
- Inductively defined equivalence of processes.
- Results.
- Spawned a new research area.
  - Papers, books, conferences, research networks. . .
  - Helped establish operational reasoning.

Bisimulation

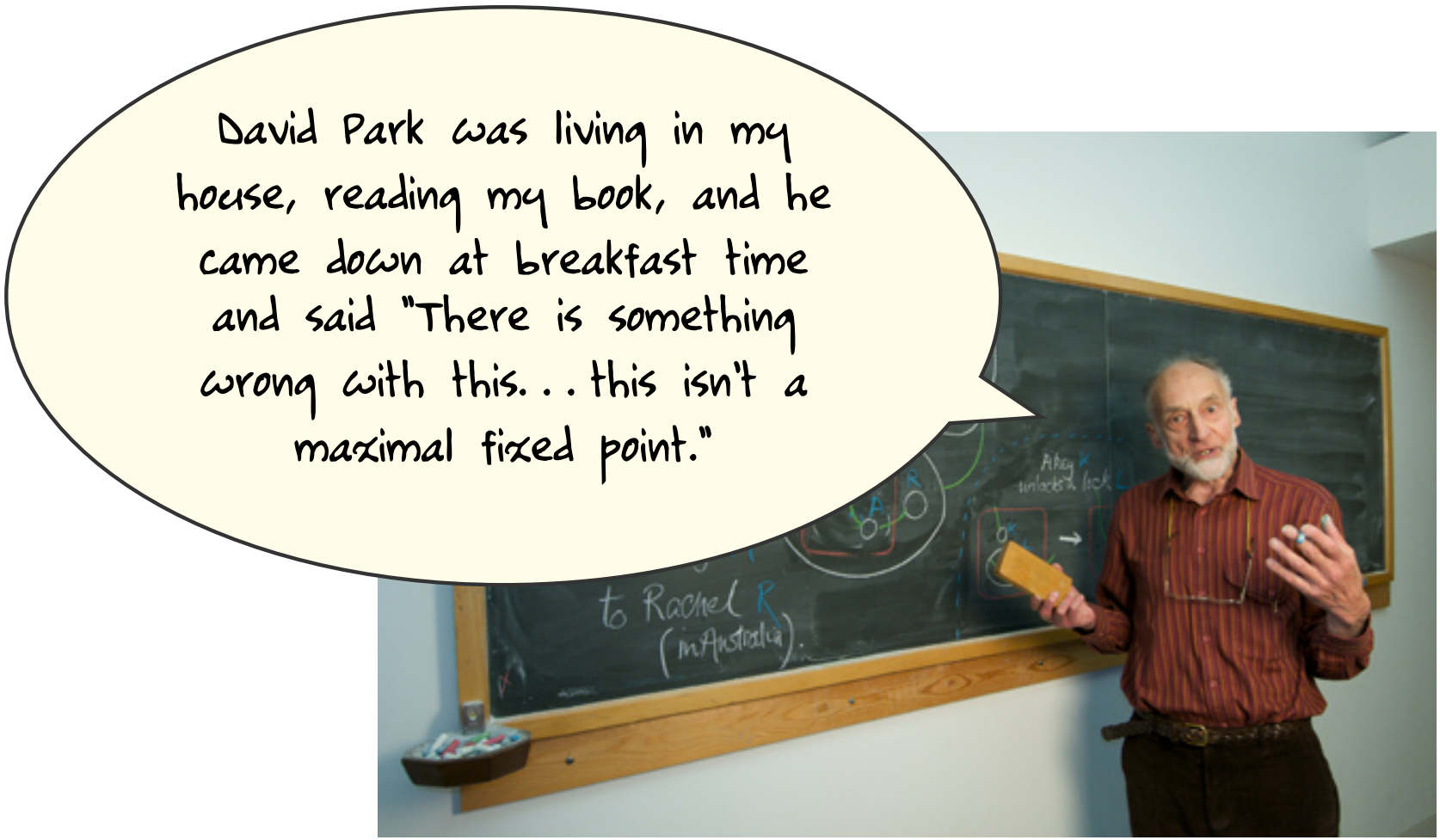


Robin Milner
Communication and Concurrency

PRENTICE HALL INTERNATIONAL SERIES IN COMPUTER SCIENCE

C.A.R. HOARE SERIES EDITOR

The most important breakfast in computer science?



Communication and Concurrency

- Technical problem: stratified bisimulation is not a fixed point.
  - $\sim_\omega$ is not always $\sim_{\omega+1}$.
  - Technical fix: transfinite induction.

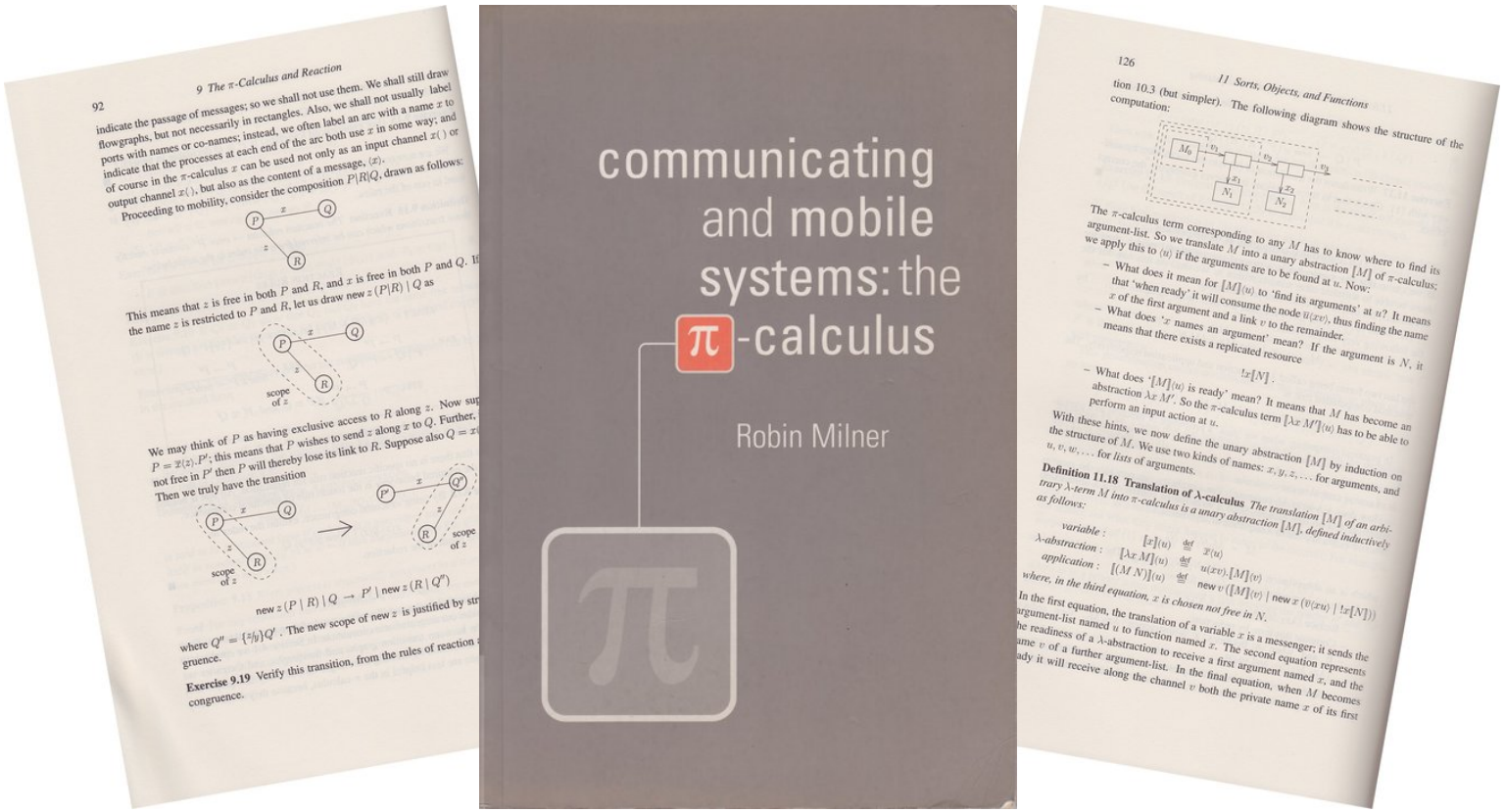
Communication and Concurrency

- Technical problem: stratified bisimulation is not a fixed point.
- More importantly, missed an important proof technique.
  - A relation $\mathcal{R}$ is a *bisimulation* whenever, for all $P \mathcal{R} Q$ and α:
    - If $P \xrightarrow{\alpha} P'$ then, for some Q', $Q \xrightarrow{\alpha} Q'$ and $P' \mathcal{R} Q'$.
    - If $Q \xrightarrow{\alpha} Q'$ then, for some P', $P \xrightarrow{\alpha} P'$ and $P' \mathcal{R} Q'$.
  - *Bisimilarity*, written $P \sim Q$, is the largest bisimulation.
  - Bisimilarity comes with a proof technique: establish a bisimulation.

Communication and Concurrency

- Technical problem: stratified bisimulation is not a fixed point.
- More importantly, missed an important proof technique.
- Bisimulation has impact far outside concurrency.
  - Coinduction and coinductive datatypes (e.g. streams).
  - Applicative bisimulation for λ-calculi.
  - Coinduction in mechanized proof systems (e.g. Coq and Agda).
  - Non-wellfounded set theory.

Naming



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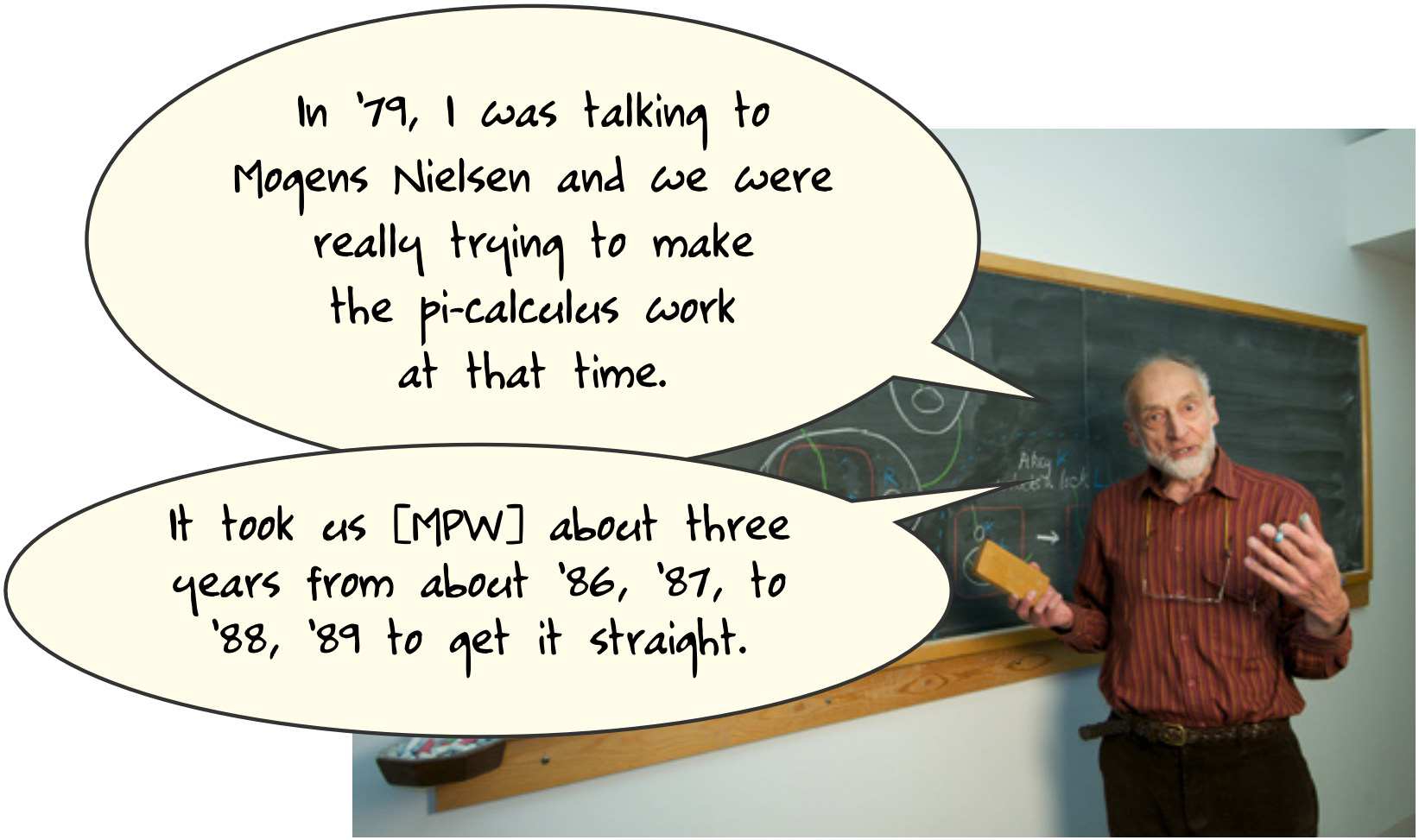

Communicating and Mobile Systems

- Old problem: gensym.
  - In the Calculus of Communicating Systems, channel scope is static.
  - Cannot model systems with *link mobility*, where channels escape.
  - Causes problems modelling functions, objects, references. . .

Communicating and Mobile Systems

- Old problem: gensym.
- Nielsen and Engberg (1986) *Extended CCS*.
  - Name generation modelled by α-equivalence.
  - Scope extrusion: $P \mid \nu(x)Q \sim \nu(x)(P \mid Q)$ when $x \notin \mathsf{fn}(P)$.
  - Complex: names, variables, constants.

Communicating and Mobile Systems

- Old problem: gensym.
- Nielsen and Engberg (1986) *Extended CCS*.
- Berry and Boudol (1990) *Chemical Abstract Machine*.
  - Reduction semantics up to a structural congruence:

$$\frac{P \equiv Q \to Q' \equiv P'}{P \to P'}$$

Communicating and Mobile Systems

- Old problem: gensym.
- Nielsen and Engberg (1986) *Extended CCS*.
- Berry and Boudol (1990) *Chemical Abstract Machine*.
- The π-calculus: Milner, Parrow & Walker (1989), Milner (1992).
  - In 1989, an LTS semantics, with scope extrusion as a bisimilarity.
  - In 1992, a reduction semantics up to a structural congruence.
  - Scope extrusion and α-equivalence *in the structural congruence*.
  - Natural embedding of a λ-calculus with explicit substitutions.

Communicating and Mobile Systems

- Old problem: gensym.
- Nielsen and Engberg (1986) *Extended CCS*.
- Berry and Boudol (1990) *Chemical Abstract Machine*.
- The π-calculus: Milner, Parrow & Walker (1989), Milner (1992).
- Wide applicability of π-like techniques:
  - Business processes.
  - Distributed systems.
  - Molecular biology.
  - Nominal set theory.
  - Objects.
  - References.
  - Security.
  - ...

Thank you Robin!