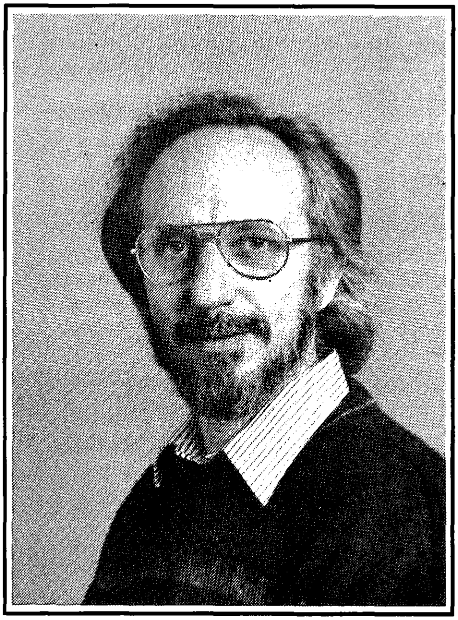

BEYOND THE MASTER NARRATIVE: TALES OF THE CREATION OF AUTOMATIC CONTROL

Christopher C. Bissell

1. Introduction

Automatic control is one of the key technologies of modern industrialised society. Like most contemporary technologies, it has a complex history, and this history can be recounted in many different ways. In this lecture I aim to examine the development of control engineering over the crucial period 1930 to 1950, taking into account some recent trends in the history of technology.

The fully-fledged, independent discipline of control engineering emerged only in the period since the Second World War, yet its roots go back to antiquity: rudimentary water level control systems, for example, are well attested in the classical world. More sophisticated feedback devices appeared with the maturing of industrial technology in post-medieval Europe. The celebrated furnace temperature control system of Cornelis Drebble dates back to the early 17th century, for example; while windmill control devices, the centrifugal governor, and the early hydraulic servomechanisms associated with steam power on ships and elsewhere appeared in the eighteenth and nineteenth centuries. By the first few decades of the twentieth century increasingly sophisticated instrumentation and control systems were deployed for process control and mechanised assembly, prime mover and electrical regulation, and flight and ship control. On the eve of the Second World War, it seems (with hindsight at least), the new discipline of automatic control was waiting in the wings, lacking only the impetus of the 'fire control' problem (gun servomechanisms) to bring it on to centre stage. Wartime military research brought together engineers from various disciplines to work on this 'fire control' problem, applying fundamental ideas from telecommunications and electrical engineering to the servomechanisms used for gun aiming. The result was the techniques of classical frequency response feedback loop design that are still widely used today, associated with the theoretical results of Bode, Nyquist, Nichols, Evans, and so on.

Such, in essence, is the 'technical' story often told of the history of automatic control. A version of it commonly appears in introductory textbooks. Table 1 derives from Dorf (1989), while Table 2 is taken from the endpapers of Franklin et al (1991). While they differ in their emphasis (Dorf stresses inventions and processes, while Franklin et al give pride of place to control theory), the picture is of discovery and invention, of great theoretical strides, and of continuous progress towards our current state of knowledge. In this lecture I shall explore in some detail the assumptions and shortcomings of this picture of the history of control engineering, with particular reference to the midtwentieth century. But before I do so, a few words on recent trends in the history of technology in general are in order.

1769	●	Watt steam engine and governor
1800	●	Whitney's interchangeable parts for musket manufacture
1868	●	Maxwell's stability analysis of a centrifugal governor
1913	●	Henry Ford's mechanised assembly for automobiles
1927	●	Black's feedback amplifier
1932	●	Nyquist stability analysis of feedback amplifier
1952	●	Numerical control of machine tools at MIT
1954	●	"Programmed article transfer" developed by Devol
1960	●	Unimate industrial robot

Table 1

1868	●	Maxwell, Flyball stability analysis
1877	●	Routh, Stability criterion
1890	●	Lyapunov, Nonlinear stability
1910	●	Sperry, Gyroscope and autopilot

1927	● Black, Feedback electronic amplifier
	● Bush, Differential analyzer
1932	● Nyquist, Nyquist stability criterion
1938	● Bode, Frequency response methods
1942	● Wiener, Optimal filter design
1947	● Hurewicz, Sampled data systems
	● Nichols, Nichols chart
1948	● Evans, Root locus
1950	● Kochenburger, Nonlinear analysis
1956	● Pontryagin, Maximum principle
1957	● Bellman, Dynamic programming
1960	● Draper, Inertial navigation
	● Kalman, Optimal estimation
1969	● Hoff, Microprocessor

Table 2

2. Approaches to the history of technology

Stuart Bennett began his 1995 Sarton Memorial Lecture by commenting on some recent developments in the historiography of technology, and it is worth considering current approaches in a little more detail. (The following discussion is taken from Bissell & Bennett, 1997.)

Traditionally, the great ideological divide in the history of science and, to a lesser extent, the history of technology has been that between the internalist and externalist approaches. As the names imply, the internalist historian concentrates on the internal history of the development of artefacts or ideas within a discipline (or sub-discipline), while the externalist is more concerned with the relationship of the discipline to the external world of politics, religious belief, social structure, and so on. In recent years the internalist/externalist controversy has become rather muted. Many, if not most, historians of technology now acknowledge the need for a 'contextualist' approach - that is, a historiography which is concerned with all the 'various political and cultural constituencies in the historical process and with the tensions and conflicts between them'

(Smith & Marx, 1994, p.259). Still vigorous, however, is the (sometimes acrimonious) debate between those of a more or less 'hard' determinist persuasion, who believe that it is predominantly science and technology which drive social change and thus historical development, and those who consider it more productive to view science and technology themselves as social constructs, and to study them as such in both their contemporary and historical manifestations. The former view is often characterised by the terms "technological determinism" or "autonomous technology", while the latter has become known as "social constructivism". For an introduction to social constructivist ideas see, for example, Bijker (1987, 1995) and Collins (1985), while a thorough examination of the various shades of technological determinism in the historiography of technology can be found in Smith & Marx (1994).

A further important trend of the last fifteen years or so has been the 'system builders' approach to the history of technology, a seminal work being *Networks of Power,* by Thomas Hughes (1983). Such historians view attempts to create large-scale, sociotechnical systems as major determinants of technological change. For example, in *Networks of Power*, Hughes argues that much of the technical change in the early years of this century was a consequence of the building of the electricity supply network, and that the form the new technology took was determined as much by decisions of the financiers and entrepreneurs who wanted to control the networks as by technical issues. He argues that the drive to create such large-scale, socio-technical systems leads to what he terms 'reverse salients' or 'impasses' - that is, areas in which crucial system development is hindered by a lack of technical knowledge or understanding. The term 'reverse salient' comes from military usage, denoting the situation which develops when the advance of an army is held up at one part of the front as the rest of the army moves forward. For Hughes and historians of a similar persuasion, the drive to develop and extend a given large-scale technical system results in massive investment of resources in order to eliminate or by-pass such a reverse salient.

So where does all this leave the poor student of the history of technology? History, like many other academic disciplines, has been greatly influenced by developments in postmodernist thinking. Just as students of literature have had to engage with the problem of the 'loss of the canon' - that is, attacks on the notion of a single, 'great tradition' (to use F.R. Leavis's phrase) - so historians have had to come to terms with the shortcomings of writing history as a single story, as a 'master narrative'. Most historians of technology are now agreed that history can rarely, if ever, be told as a simple, linear, narrative, based on any single point of view. Rather, there are many, complex, interwoven stories. Indeed, some historians would even reject the use of the word 'history' in the singular. Histories of technology, then, like our current world are messy; they are local, sited and contingent in either or both time and space. The historian's task, as Philip Scranton (1994) has argued, is to unravel the conjunctural complexities. In this spirit, then, let us try to do this for a few (hi)stories of how automatic control emerged as a separate engineering discipline. In particular, we shall consider

- technical stories
- institutional stories
- a cultural-linguistic story
- cultural-political stories

3. Technical stories

As already implied in Tables 1 and 2, the leitmotiv of technical stories is that of continuous progress - and, indeed, there has been an astounding technical achievement over the past decades. Within fifty years, the fairly rudimentary control systems of the early part of the century evolved into large-scale process plant management systems; high performance computer disc drive or robot arm controllers; automobile automatic braking systems; and so on. Accepting, for the moment, the ethos of Tables 1 and 2, we might be tempted to expand it (for the period 1925-1950) as Table 3.

So what are the major characteristics of the technical story of Table 3? To begin with, closer inspection reveals that it is not one, but a number of interlinked, technical stories: the single chronology is quite tendentious. Consider, for example, the italicised entries. These feature rarely, if at all, in either the secondary English-language literature of the history of the discipline or in the potted histories contained in English-language undergraduate textbooks. Russian and German stories, on the other hand, take a significantly different view - often emphasising, as might be expected, the native contributions of those cultures to the technical development of control engineering. Second, Tables 1 - 3 stress theory, a linear chronological development, technical successes (failures do not feature at all); they concentrate on the achievements of great men (no women); and they give an impression of uninterrupted technological progress. These are common characteristics of technical stories of the development of a particular discipline; and if one particular story ultimately wins out (as might be claimed, perhaps, for the American version in the case of classical control engineering), the competing stories are soon neglected, marginalised, or completely forgotten. Bearing this in mind, the historian of automatic control interested in exploring the process of technological change might usefully look at some alternative stories, and we shall proceed to do this now.

1927	● Black's feedback amplifier
1928	● *Küpfmüller's work on control system stability*
1932	● Nyquist's analysis of feedback amplifier stability
1934	● Hazen's work on servos for differential analysers
1936	● *Mikhailov's application of Nyquist's results to control systems*
1937	● Taplin's use of the 'closed-loop' transfer function
	● *Oppelt's generic description of control systems*
1940	● *Leonhard's application of Nyquist's results to electrical regulation*
The war years	● Frequency response approach to control system design (USA/UK)
	● A generic systems approach (USA/UK/Germany)
	● Development of approaches to stochastic modelling (USA/USSR)
	● Tools for the analysis of sampled-data systems (USA/UK/USSR)
	● *Andronov's approach to non-linear control system analysis*

1948	• Evans's root locus approach
late 1940s/ early 1950s	• Work on sampled-data systems by Hurewicz, Jury, Ragazzini (USA), *Tsypkin (USSR), Tustin (UK)*
	• Describing function approach of *Dutilh (France), Goldfarb (USSR),* Kochenburger (USA), *Tustin (UK)*

Table 3

4. Institutional stories

The professional institutions have played a major role in the development of engineering in the twentieth century. From the mid-1930s onwards, engineering institutions in various countries started to take a professional interest in automatic control. Table 4 lists some of the important events. It is interesting to compare this with Table 3. At first sight, there is considerable agreement in the chronology: the first specialist groupings in the mid- to late-1930s in the USA, Germany and the USSR, for example, coincide in time with the published work of Black, Bode, Mikhailov, Nyquist, and Oppelt. Yet the theoretical work was largely unknown, or not considered particularly relevant, to most practising engineers and the participants in these early institutional groups. The exigencies of industrial control problems, rather than the theoretical work taking place in the highly specialised fields of telecommunications, servomechanisms for differential analyzers, or autopilot design, provided the initial driving force for the institutions, particularly in the ASME and VDI groups - and even during the war years. And whereas Tables 1 - 3 might suggest a direct line from research to practice, with a radical change in thinking as the new discoveries, techniques and theories emerged, then the institutional stories demonstrate a greater continuity with the past. These (rather conservative) bodies tended to preserve their traditions, defending their positions, adapting slowly, absorbing and codifying developments. It is worth singling out four themes from the institutional history.

1. Work on terminology and standardization. This started before the war in both the USA and Germany and continued, rather surprisingly,

throughout the hostilities. The British Servo-Panel, a loose wartime organisation founded in 1942 to promulgate developments in servomechanisms, also took terminology very seriously.

2. Institutional structures. The uncertain status of the new discipline in immediate postwar years is well illustrated by the rapidly changing committee structure of the American Institute of Electrical Engineers, of which 29 committees or subcommittees concerned themselves at some point or other with automatic control during the period 1945-1957 (the field became the province of a single committee only in 1960; for details see Bennett, 1976). The contrast to the linear technical stories is striking; the impression gained is of considerable confusion; of attempts to absorb the new area into existing structures (often involving suspicion between groups, and associated political infighting); and of a lack of understanding of the generic nature of automatic control. Other institutions dealt with the problem in different ways, but supporting the new discipline proved problematic in a number of countries (less so in continental Europe, with their unitary bodies, than in, say, North America and the UK).

3. Technical conferences. These had a great influence in bringing together international players in control engineering, and drawing together the disparate developments of the wartime years. Landmark events include the Cranfield Conference of 1951 (the first international conference on automatic control); the New York Conference of 1953; the Heidelberg conference of 1957; and the Moscow Conference (the first IFAC meeting) of 1960.

4. Links between the professional bodies and governments. Such links had been established in the Allied countries during the war, and continued after hostilities ceased. The Cranfield Conference, for example, was organised by the British government, in collaboration with the IEE and IMechE.

1934	●	Special Soviet Commission on Remote Control & Automation
1936	●	ASME Industrial Instruments & Regulators Committee

1939	VDI Control Committee formed
	Soviet Institute of Automation & Remote Control Formed
1940	First Soviet All-Union Conference on Automatic Control
	US National Defense Research Committee formed
1942	British Servo-Panel established
1944	British and German glossaries published
1946-7	First IEE conferences on control topics
1949	First part of British Standard 1523 issued
	AIEE Servomechanisms Committee
1950	Control Section of Society of Instrument Technologists established
1951	IRE Technical Committee on servo-systems formed
	Cranfield International Conference
1952	ASME Dynamic Systems Committee formed
	AIEE/ASME/ASA terminology published
	DIN standard
1953	New York Conference
1954	Soviet Glossary published
	Joint VDE/VDI conference on applications in economics
1956	Heidelberg Conference
	IFAC established

Table 4

The institutional stories add a new dimension to the technical stories told earlier. Note that they imply a greater range of coexisting narratives than the former. This is hardly surprising. Professional institutions are embedded in different national cultures; their histories reflect this cultural diversity as well as the social dimension of technology, while purely technical stories tend to hide both.

5. A cultural-linguistic story

The terminological activities of the various professional institutions have already been mentioned, and it is productive to view these activities as part of a more general phenomenon - what might be called a cultural-linguistic story. This is the tale of the emergence and acceptance of a radical new language for system modelling and design; it is the story of using a new language, learning to asking new questions, and doing new things. As Thomas Kuhn has put it (Kuhn, 1970):

> Examining the record of past research from the vantage of contemporary historiography, the historian of science may be tempted to exclaim that when paradigms change, the world itself changes with them. Led by a new paradigm, scientists adopt new instruments and look in new places. Even more important, during revolutions scientists see new and different things when looking with familiar instruments in places they have looked before.

So, for example, as a result of the wartime 'control engineering revolution', engineers began to see generically related systems where formerly they had seen quite separate mechanical, electrical or chemical processes. They began to see signal and information flows where formerly there had been only mechanical linkages or the flow of energy and materials. Such radical changes in thinking were neither sudden nor easy. The author recently had the opportunity to discuss this with a number of engineers who were closely involved with control engineering in the 1940s and 1950s. Their recollections are illuminating:

> Systems theory emerged very slowly and really in a quite anonymous way - no single person was responsible. We also devoted a lot of time and effort to this aspect in the specialist VDI committee. But the development of systems thinking came about very slowly, as a part of group discussion... It was a long time before the general applicability of control concepts was understood... The shift from a "communications way of thinking" to a much more general "control way of thinking" was the fundamental step...
>
> (Winfried Oppelt, interview, 1991)

> I think my personal realisation [of systems ideas] came as I worked with control systems which consisted of a number of operations in sequence - the fire control problem was classic, of course, with target detection, tracking, prediction, and gun laying. As we worked on such systems, combining the responses of the various elements to get the total response, it became natural to think in general system terms, applying identical methods even though one element might be electrical, another mechanical, hydraulic or even human.
>
> (Arnold Tustin, interview, 1991)

> When I got into control engineering, there were many different approaches to solving a control problem: rules for turbine control, other rules for temperature control, and so on, which had little to do with each other. You can't really talk of any 'systems thinking' at that time. Our achievement was to recognise the commonality, to bring everything together, to use the same language and the same symbols. In this way 'systems thinking' came about automatically. That would have been just before the war.
>
> (Hans Sartorius, interview, 1994)

In many ways, the creation of the new discipline of automatic control was the creation and acceptance of this new language. It is striking that discussions of papers presented at technical meetings immediately after the war included reference after reference to 'the need for translation' in order for engineers from different disciplines to be able to understand one another. Many quite eminent engineers were unhappy with the emerging new language, which they saw as unfamiliar and unnecessary (for full bibliographic details of the following citations see Bissell, 1994 & 1996):

> The experts in the servomechanism and control fields are unfortunately not exceptions to the rule that the experts in an art always ball up the terminology and notation until they can be followed only by a like expert ... At least the [process engineer] can directly express a ratio of effect to

> cause ... without becoming involved in the width of a hypothetical frequency transmission band and in such acoustical abstraction as dB per octave.
>
> (Ed Smith, 1946)

> [The various fields of automatic control] have developed separately, and those concerned have developed their own terminology and philosophy. The approach is different in each case, and it is going to be extremely difficult, I think, to effect a reconciliation [...] the approach which seems to be quite suitable for servo mechanisms and industrial regulators causes us considerable difficulty, so far as out process control work is concerned; and in order to understand the paper fully we have to translate it into entirely different language.
>
> (G.H. Farrington, 1947)

> The fact that at least four largely independent developments of the theory of automatic control have been made [prime mover governors; pneumatic process controllers; electronic feedback amplifiers; and wartime fire-control servomechanisms] has naturally resulted in a great confusion of nomenclature. It requires a feat of translation for the chemical engineer to profit from the stockpiles of clarification and invention which the mechanical engineer, the communication engineer, and the electrical power engineer has built up, and the same applies in the reverse direction.
>
> (A. Tustin, 1950)

These remarks are contemporaneous with the publication of the first textbooks on control engineering, textbooks which form a vital part of the cultural-linguistic story. Again, Kuhn (1970) has made a perceptive observation:

> Textbooks have to be rewritten in whole or in part in the aftermath of each scientific revolution, and, once rewritten,

> they inevitably disguise not only the role but the very existence of the revolutions that produced them.

The early textbooks on servomechanisms and automatic control did not simply describe the work that had been carried out during the war, they created it anew. The American books of the late 1940s in particular were responsible for creating or disseminating many aspects of an approach we still use today: the Nichols chart; frequency-response design methods; conversion between step-response and frequency response as a measure of control loop quality; and so on. The new approach was quickly promulgated in the engineering profession, with the rapid translation of many seminal works into major world languages (Table 5 indicates some of the earliest of these). Given the remarks just quoted, we might even speak of 'translation' both within a single language, and from one language to another.

The way that control engineering theory and techniques became public rather suddenly after the secrecy of the war years had made contemporary engineers - for a brief period at least - highly aware of the linguistic dimension to their work. It is interesting to note, however, that once agreement had been reached on language and conventions, the conceptual difficulties and arguments demonstrated in the preceeding quotations appeared to fade away. The specific, cultural-linguistic story just identified thus brings to light an all too often neglected dimension of the historical development of automatic control.

1944	● Oldenbourg & Sartorius *Dynamik selbsttätiger Regelungen*
	● Lossievskii *Avtomaticheskie Regulyatory*
	● Smith *Automatic Control Engineering*
1945	● MacColl *Fundamental theory of servo-mechanisms*
	● Bode *Network Analysis and Feedback Amplifier Design*
1946	● Eckman *Principles of Industrial Control*
1947	● James et al *Theory of servomechanisms*
	● Lauer, Lesnick & Matson *Servomechanism Fundamentals*
	● Oppelt *Grundgesetzte der Regelung*
	● Russian translation of *MacColl*
1948	● Brown & Campbell *Principles of Servomechanisms*

	English translation of *Oldenbourg & Sartorius*;
	Russian translations of *Bode; Lauer et al; Oldenbourg & Sartorius*
1951	Russian translation of *James et al*

Table 5 (For references and more details see Bissell, 1996)

6. Cultural-political stories

All the stories I have considered so far have been located primarily within the control engineering community. But there are other stories of the emergence of the discipline which can be told only in a much broader cultural and political context. As illustrations, let me briefly examine two such stories, set in the immediate post war period in the USA and USSR respectively (see Bissell, 1996, for further details).

6.1 An American tale

By the closing days of the Second World War, US government scientific advisors were in no doubt about the importance of science and technology in the post-war world. In his report to President Roosevelt, *Science: The Endless Frontier*, Vannevar Bush recommended that the US Government should accept new responsibilities for promoting the flow of scientific knowledge: "These responsibilities are the proper concern of the Government, for they vitally affect our health, our jobs, and our national security. It is in keeping also with basic United States policy that the Government should foster the opening of new frontiers and this is the modern way to do it." A vigorous debate ensued over precisely how science and technology should be officially promoted, but that there should be such government intervention was disputed less and less. And this trend is clear in the way that automatic control was codified and presented to the wider engineering community through the writings of American control engineers.

For example, in the preface to his *Fundamental Theory of Servomechanisms*, LeRoy MacColl explained how Warren Weaver, Chief of the Applied Mathematics Panel of the National Defense Research Committee, had asked him to write a general expository paper on the theory of servomechanisms and that it was ultimately decided that "the purpose of the work, *as a contribution to the war effort* [my italics], would be better served if it were to appear in book form". So even before the war ended, there was a concerted, directed effort in the United States to set down the technological achievements of the war years - for military and political reasons, as well as scientific ones. Deriving initially from the war effort itself, such publications soon became part of an open *post-war* push towards technological supremacy, in which the United States was to pick up the European mantle as the intellectual driving force of science and technology. One aspect of this political dimension was the continuing high level of official support for the promulgation of the wartime technical achievements of the United States. Perhaps the most impressive outcome in this area was the MIT Radiation Laboratory Series of texts. These formed a 27-volume monument to (predominantly American) wartime technological achievement in electronics, radar, control engineering, and so on. They were also a clear political statement about the technological role the United States was to play in the post-war world. But before making further comment on this, let us move on to the Soviet tale.

6.2 A Soviet tale

A key figure in immediate post-war Soviet control engineering was A.A. Andronov, whose interest in control had developed from his earlier work on non-linear dynamics. In 1944 he established a 'seminar' at the Institute of Automation and Remote Control in Moscow, which was of crucial importance for the development of modern control theory in the USSR. Unusually, the particular story I wish to relate also involves the study of the history of science and technology as an academic discipline.

During the late 1940s, Andronov and some of his colleagues developed a keen interest in non-linear control problems in both their contemporary manifestations and in the context of early work by the nineteenth century St Petersburg engineer, I. A. Vyshnegradskii. In collaboration with I. N. Voznesenskii, Andronov produced a critical edition of early control engineering writings by J. C. Maxwell, Vyshnegradskii himself, and Aurel Stodola (the engineer responsible for drawing the attention of Adolf Hurwitz to the stability problem). Andronov & Voznesenskii's book became well known in the USSR, and most of the post-war generation of Russian control engineering textbooks included Vyshnegradskii's technique for assessing stability, sometimes extended to higher-order systems, alongside the classical control methods of the 1930s and 1940s. Indeed, Vyshnegradskii's work was often presented as the first step in a continuous progression leading ultimately to the Mikhailov and Nyquist criteria, and to the technique developed by Neimark and others in the late 1940s in the Soviet Union known as D-partition or D-decomposition.

In the immediate post war period in the Soviet Union, the history of science and technology had taken on a new ideological significance. During the war, the alliance against Germany had encouraged an outward-looking approach to the history of science. For example the 300th anniversaries of the death of Galileo and the birth of Newton in 1942 and 1943 respectively, and the 400th anniversary of Copernicus' *De Revolutionibus* in 1943, resulted in many publications which set Russian science firmly within the European scientific tradition. With the onset of the cold war, however, attitudes changed. Until 1947, Russian historians were particularly concerned with identifying and analysing Russian contributions to international science. After 1947, and in particular after a conference on 'national Russian science' in January 1949, historians were discouraged from indicating inconsistencies and digressions in pre-Soviet Russian science and were encouraged to emphasise the pristine purity of national sources, often with quite spurious claims for priority of invention and theory (Vucinich, 1984).

The genesis and publication of Andronov's historical writings on the history of control coincided almost precisely with this hardening political atmosphere. His own historical research, while it stressed the importance of early Russian work on the control of prime movers, did not suffer from the downright xenophobia of much contemporary Soviet writing on the history of science and technology - even if some of his conclusions are a little tendentious.

It seems highly likely that the historical interests of Andronov's circle were acceptable only because they were consistent with the political post-war imperative of re-defining Russian science and technology. The right sort of historical investigation could be pursued with confidence - and, in the case of automatic control, could be used explicitly to legitimate teaching and research in a technological discipline which turned out to have an excellent native pedigree.

Both the American and Russian tales illustrate well how the immediate post-war development of automatic control - even in such apparently apolitical areas as the writing of textbooks - was closely linked to ideology and national cultures. Even the *theory* of automatic control is not value free!

7. Conclusion

We have come a long way from the picture of control history presented at the beginning of this lecture, with its focus on dates, inventions and theory. Taking time to look at some other narratives has brought into clearer focus the social, political and even linguistic dimensions of the history of the discipline. Historians of technology can take comfort in this. Abandoning the master narrative is no barrier to researching or relating the histories of technology. Indeed, examining the multiplicity of interwoven stories sheds light on technological development in a way that no single, master narrative can.

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