Spring 2022 – Systems Biology of Reproduction
Discussion Outline (Systems Biology)
Michael K. Skinner – Biol 475/575
Weeks 1 and 2 (January 20, 2022)

Systems Biology

Primary Papers

1. Westerhoff & Palsson (2004) Nat Biotech 22:1249-1252
2. Joyner (2011) J Appl Physiol 111:335-342
3. Stanoev, et al. (2021) Development 148:dev197608

Discussion

Student 1 - Ref #1 above
-How does this support evolutionary systems biology?
-What was the convergence discussed?
-Give an example that supports this perspective.

Student 2 - Ref #2 above
-What is the problem with reductionism?
-What is the void?
-What is the solution?

Student 3 - Ref #3 above
-What is robustness?
-What is the role of inhomogeneous steady state?
-What insights in the systems biology of cellular differentiation are described?

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The evolution of molecular biology into systems biology

Hans V Westerhoff[1] & Bernhard O Palsson[2]

Systems analysis has historically been performed in many areas of biology, including ecology, developmental biology and immunology. More recently, the genomics revolution has catapulted molecular biology into the realm of systems biology. In unicellular organisms and well-defined cell lines of higher organisms, systems approaches are making definitive strides toward scientific understanding and biotechnological applications. We argue here that two distinct lines of inquiry in molecular biology have converged to form contemporary systems biology.

Whereas the foundations of systems biology-at-large are generally recognized as being as far apart as 19th century whole-organism embryology and network mathematics, there is a school of thought that systems biology of the living cell has its origin in the expansion of molecular biology to genome-wide analyses. From this perspective, the emergence of this 'new' field constitutes a 'paradigm shift' for molecular biology, which ironically has often focused on reductionist thinking. Systems thinking in molecular biology will likely be dominated by formal integrative analysis going forward rather than solely being driven by high-throughput technologies.

It is, however, incorrect to state that integrative thinking is new to molecular biology. The first molecular regulatory circuits were mapped out over 40 years ago. The feedback inhibition of amino acid biosynthetic pathways was discovered in 1957 (refs. 1,2), and the transcriptional regulation associated with the glucose-lactose diauxic shift led to the definition of the *lac* operon and the elucidation of its regulation[3]. With the study of these regulatory mechanisms, admittedly on a small scale, molecular biologists began to apply systems approaches to unravel the molecular components and logic that underlie cellular processes, often in parallel with the characterization of individual macromolecules. High-throughput technologies have made the scale of such inquiries much larger, enabling us to view the genome as the 'system' to study. Thus, the popular contemporary view of systems biology may be synonymous with 'genomic' biology.

This article discusses two historical roots of systems biology in molecular biology (**Fig. 1**). Although we briefly outline the more familiar first root—which stemmed from fundamental discoveries about the nature of genetic material, structural characterization of macromolecules and later developments in recombinant and high-throughput technologies—more emphasis is placed on the second root, which sprung from nonequilibrium thermodynamics theory in the 1940s, the elucidation of biochemical pathways and feedback controls in unicellular organisms and the emerging recognition of networks in biology. We conclude by discussing how these two lines of work are now merging in contemporary systems biology.

Scaling-up molecular biology

In the decades following its foundational discoveries of the structure and information coding of DNA and protein, molecular biology blossomed as a field, with a series of breathtaking discoveries (**Fig. 1**). The description of restriction enzymes and cloning were major breakthroughs in the 1970s, ushering in the era of genetic engineering and biotechnology. In the 1980s, we began to see the scale-up of some of the fundamental experimental approaches of molecular biology. Automated DNA sequencers began to appear and reached genome-scale sequencing in the mid-1990s[4,5]. Automation, miniaturization and multiplexing of various assays led to the generation of additional 'omics' data types[6,7].

The large volumes of data generated by these approaches led to rapid growth in the field of bioinformatics, again largely emanating from the reductionist perspective. Although this effort was mostly focused on statistical models and object classification approaches in the late 1990s, it was recognized that a more formal and mechanistic framework was needed to analyze multiple high-throughput data types systematically[8,9]. This need led to efforts toward genome-scale model building to analyze the systems properties of cellular function.

Molecular self-organization

Even before the first key events in the history of molecular biology, several lines of reasoning revealed that integration of multiple molecular processes is fundamental to the living cell. Biochemical processes necessitate the production of entropy (chaos in the thermodynamic sense) as driving force. The paradox felt by many, but expressed by Schrödinger in his war-time lectures[10], was how one could explain the progressive ordering that occurs in developmental biology (that is, the 'self-organization,' decrease in chaos) when entropy ('chaos') must be increased.

The answer was that one process could produce order (negative entropy or negentropy) provided it was coupled to a second process that produced more chaos (entropy): coupling, another word for integration of processes, is therefore essential for life. Onsager[11] provided the basis for this concept by stressing the significance of the coupling of dissimilar processes. He is also relevant because he discovered a law for such systems of coupled processes: close to equilibrium the dependence of the one process rate on the driving force of the other process should equal the dependence of the other process rate on the

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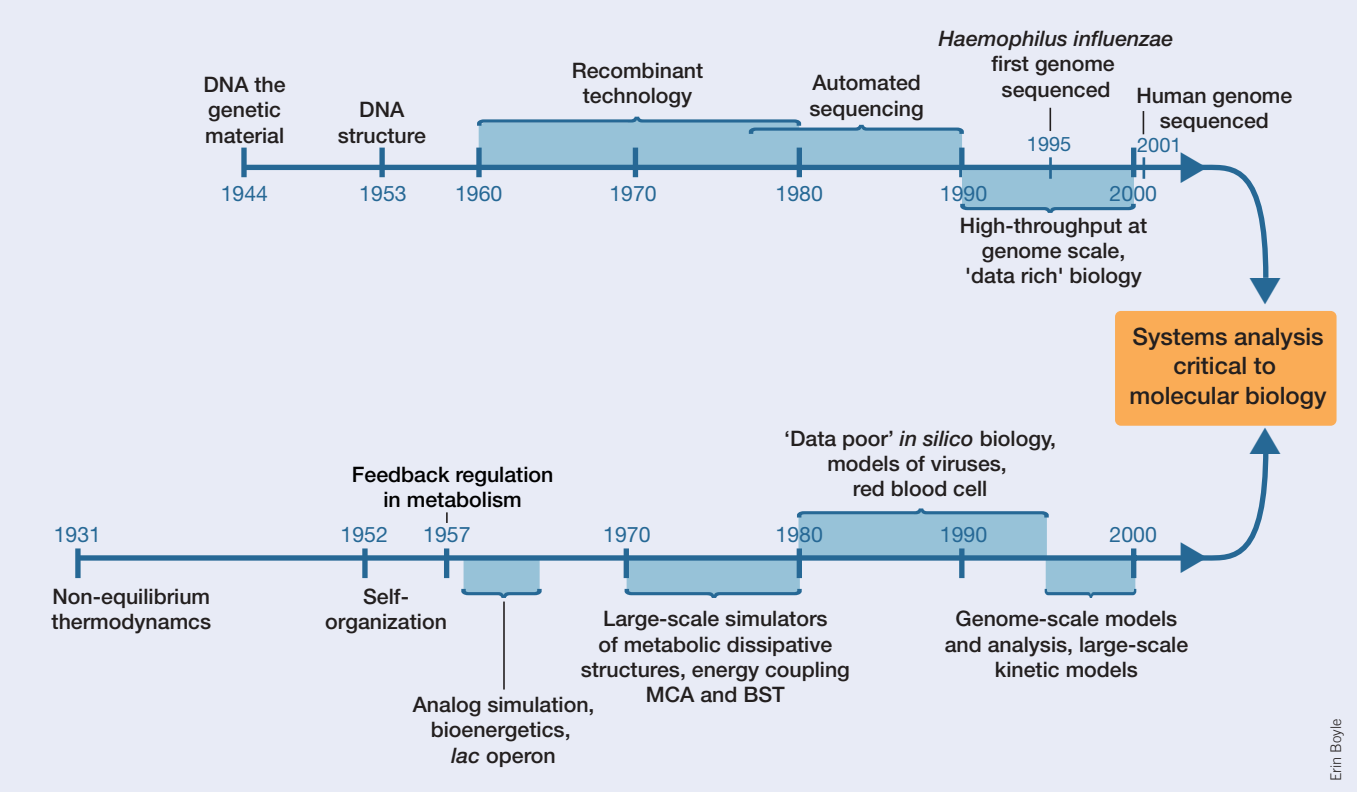

Figure 1 Two lines of inquiry led from the approximate onset of molecular biological thinking to present-day systems biology. The top timeline represents the root of systems biology in mainstream molecular biology, with its emphasis on individual macromolecules. Scaled-up versions of this effort then induced systems biology as a way to look at all those molecules simultaneously, and consider their interactions. The lower timeline represents the lesser-known effort that constantly focused on the formal analysis of new functional states that arise when multiple molecules interact simultaneously.

former driving force. Caplan, Essig and Rottenberg[12] later defined a coupling coefficient, which quantifies the extent to which two processes are coupled in a system and showed that this coefficient must range between 0 and 1.

These approaches were called nonequilibrium thermodynamics and constituted a prelude to systems biology at the cell and molecular levels in that they (i) dealt with integration quantitatively and (ii) aimed to discover general principles rather than just being descriptive. An improved procedure for describing ion movement and energy transduction in biological membranes, termed mosaic nonequilibrium thermodynamics, further progressed towards systems thinking in that it (iii) established a connection to molecular mechanisms and (iv) enabled the determination of the stoichiometry of membrane energy transduction from system data[13]. Peter Mitchell's[14] chemiosmotic coupling principle was another early case of systems analysis in cell and molecular biology. It stated that ATP synthesis was coupled in quite an indirect way to respiration, involving an entire intracellular system, including a volume surrounded by an ion-impermeable membrane and proton movement across it. Indeed, for eukaryotes, this provided much of the rationale for the organization of the mitochondrion. In his calculations verifying that that the proposed chemiosmotic mechanisms transferred sufficient free energy to empower ATP synthesis, Mitchell demonstrated the sort of quantitative thinking that would eventually prove crucial to the study of biochemical systems[14].

The problem of biological self-organization was to understand how structures, oscillations or waves arise in a steady and homogenous environment, a phenomenon called symmetry breaking. Turing[16] led the way, but the Prigogine school[17] and others developed the topic from the perspective of nonequilibrium thermodynamics in molecular contexts such as biochemical reactions involved in sugar metabolism (glycolysis). They demonstrated how having a sufficient number of nonlinearly interacting chemical processes in a single system such as the Zhabotinski reaction, a developing tissue, or glycolysis, could lead to symmetry-breaking as a result of self-amplification of random fluctuations. Of course, more recent molecular developmental biology studies have shown that reality is even more complicated; prespecification by external (maternally specified) gradients of morphogens may substitute for the random fluctuations, increasing the robustness of development[18]. Perhaps more importantly, Prigogine searched for and found a law (on minimum entropy production). Although it is strictly valid only in Onsager's near-equilibrium domain, it testified to the systems scientists' quest for the principles underlying systems, rather than just for their appearances.

Early on, oscillations in yeast glycolysis were the experimental systems of choice. Although intact cells were studied[19], more often measurements were made using cell extracts[20]. Reductionist biochemical thinking proclaimed that a single pacemaker enzyme should be responsible for the oscillations. Only relatively recently has systems-based analysis in one of our laboratories (H.V.W.) been used to reveal that the oscillations are simultaneously controlled by many steps in the intracellular network[21] and how the oscillations in the individual cells synchronize actively[22]. Of course, with the more recent experimental capability to inspect single cells dynamically, more and more cells are

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seen to exhibit asynchronous oscillations of all sorts and some of these cases are up for systems biology analysis. Slime mold aggregation was another early case where a network of reactions was shown to be essential for systems biology reaching one step beyond cell biology, again by combining mathematical modeling with experimental molecular information[23].

Building large-scale models

Following the events of the late 1950s and early 1960s, researchers undertook efforts that were not well publicized and formulated mathematical models to simulate the functions of newly discovered regulatory circuits in cells. Even before digital computers became available, simulations of integrated molecular functions were performed on analog computers[24]. These efforts grew in scale to dynamic simulation of large metabolic networks in the 1970s[25–27]. Following the pathway-centered kinetic models in the seventies[28], cell-scale flux models of the human red cell were published by the late 1980s (ref. 29), and by the early 1990s genome-scale models of viruses and large-scale models of mitosis were formulated[30]. With the advent of genome-scale sequencing, the first genome-scale, constraint-based metabolic models for bacteria were constructed[31]. These models describe reconstructed networks and their possible functional states (phenotypes) and are now available at the genome-scale for a growing number of organisms. They treat the 'genome' as the 'system.'

Progress toward the development of detailed kinetic models at a large scale has proven to be slower. Some of these models approach computer replicas of pathways of metabolism, signal transduction and gene expression, and are active on the web, ready for experimentation and integration (compare http://www.siliconcell.net/). Obtaining *in vivo* numerical values for kinetic constants remains a key challenge.

Metabolic control analysis

We have agreed that contemporary systems biology has an historical root outside mainstream molecular biology, ranging from basic principles of self-organization in nonequilibrium thermodynamics, through large-scale flux and kinetic models to 'genetic circuit' thinking in molecular biology. 'Systems thinking' differs from 'component thinking' and requires the development of new conceptual frameworks.

Metabolic control analysis (MCA), developed in the early seventies[28,32], presented a key example of approaches to characterize properties of networks of interacting chemical reactions. At this time, thinking in biochemistry was dominated by the concept that there had to be a single 'rate-limiting' step at the beginning of all metabolic pathways. Criteria used to establish whether a given enzyme was rate-limiting referred to it as being far from equilibrium, strongly regulated by various metabolic factors or causing pathway flux to decrease when inhibited.

However, the application of these criteria to some metabolic pathways suggested that they contained more than a single rate-limiting step. Network thinking through MCA helped to resolve this paradox. First, mathematical models of metabolic pathways were developed both for inspiration and discovery, and subsequently used to check numerically the principles they conjectured[28,32]. Second, quantitative definitions were developed to describe the extent to which a step limited the flux through a pathway. This 'flux-control coefficient' of a particular step corresponded to the sensitivity coefficient of the pathway flux with respect to the activity of the particular enzyme. Third, these investigators looked for proof of the concept that there should be a single rate-limiting enzyme in a pathway that should have a flux-control coefficient of unity, with all others having flux control coefficients of zero. Instead, they found a theorem stating that all the flux-control coefficients must sum to unity[28,32]. This result then suggested that there need not be a single rate-limiting step to a pathway and that instead many enzymes can contribute simultaneously to the control of the network. Thus, control was not a component property but a network property. The network nature of regulation was shown experimentally to be the case for mitochondrial ATP generation, where control was indeed distributed over more than three steps, and quite notably not particularly strong, neither for the first nor for the irreversible step of the pathway[33].

An important aspect of systems biology is to relate the system properties to the molecular properties of components that comprise a network. The kinetics-based sensitivity analysis by MCA, and its close relative, biochemical systems theory proposed by H.V.W and Chen[34], showed that by focusing on the properties of an individual component, one cannot properly decipher its role in the context of a whole network. The connectivity laws proven by MCA[28,34] (see other references in ref. 35) pinpointed how that distribution of control relates to network structure and the kinetic properties of all network components simultaneously. Similarly, the topological analyses of network structure by our groups[31,36] have revealed the existence of network-based definitions of pathways that can be used mathematically to represent all possible functional states of reconstructed networks[37]. Thus, a growing number of methods now exist to analyze the properties mathematically of the large-scale networks that we are now able to reconstruct based on high-throughput data.

Convergence

Figure 1 presents our interpretation of the history of systems analysis in cell and molecular biology. Events in the upper timeline have been much more to the fore of scientific thinking than those in the lower timeline. In one sense, the dazzling stream of discoveries and exciting technologies (most recently with genome-wide data) provides the 'biology' root to contemporary systems biology. In contrast, scientific progress in the lower timeline has never gained much notoriety, although work in this area was much more prominent in European science throughout this period. This latter branch might be thought of as the 'systems' root of systems biology.

Systems modeling and simulation in molecular biology was once seen as purely theoretical and not particularly relevant to understanding 'real' biology. However, now that molecular biology has become such a data-rich field, the need for theory, model building and simulation has emerged. The systems-directed root always had the ambition of discovering fundamental principles and laws, such as those of nonequilibrium thermodynamics and MCA. This ambition should now extend to systems biology.

All too often, the field has been perceived as just pattern recognition and phenomenological modeling. Systems biology is a thorough science with its own quest for scientific principles at the interface of physics, chemistry and biology, with its remarkable mixture of functionality, hysteresis, optimization and physical chemical limitations. *In silico* analysis of complex cellular processes (whether for data description, genetic engineering or scientific discovery), with its focus on elucidating system mechanisms, has in fact become critical for progress in biology.

The historical dichotomy in approaches to molecular biology must now be reconciled with the need to corral resources and expertise in systems approaches. Although the reductionist molecular biological root has been the focus of a plethora of investigations, literature sources and curricula, the same is not true for the systems molecular biology root. There is now a need for development of theoretical and

analytical approaches, curricula and educational materials to advance understanding of the systems in cell and molecular biology. Unknown to many, the 'pre-online PDF' era contains answers to many of the current challenges and pitfalls facing the field. So although systems biology has an intellectually exciting future ahead of it, the leaders in the field should try to minimize rediscovery and focus on the newer challenges facing us, particularly those that come with the application of existing concepts to genome-scale problems and identification of the new issues that arise from the study of cellular functions on this scale.

Where has this history brought us? We now have the growing and general recognition that systems analysis is important to the future evolution of cell and molecular biology. Some reeducation of workers in the field may be in order (http://www.systembiology.net/). Over the near term, it is likely that successes with practical applications of systems biology will be confined to unicellular systems. We are now seeing successful applications of systems biology to microbes, including pathway engineering (e.g., see our recent publications[37,38]), network-based drug design (e.g., H.V.W. and colleagues[39]), and prediction of the outcome of complex biological processes, such as adaptive evolution (B.O.P and colleagues[40]). Although the mathematical modeling of whole-body human systems cannot yet be linked to genome-wide data and models, data analysis and modeling are likely to contribute to the success of realizing the goal of individualized medicine. Even if we have to rely on less precise models than the currently available genome-scale models of microorganisms, systems biology may soon lead to better diagnosis and dynamic therapies of human disease than the qualitative methodology presently in use.

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COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

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Review

Edward F. Adolph Distinguished Lectureship

Giant sucking sound: can physiology fill the intellectual void left by the reductionists?

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Joyner MJ. Giant sucking sound: can physiology fill the intellectual void left by the reductionists?. *J Appl Physiol* 111: 335–342, 2011. First published June 2, 2011; doi:10.1152/japplphysiol.00565.2011.—Molecular reductionism has so far failed to deliver the broad-based therapeutic insights that were initially hoped for. This form of reductionism is now being replaced by so-called "systems biology." This is a nebulously defined approach and/or discipline, with some versions of it relying excessively on hypothesis-neutral approaches and only minimally informed by key physiological concepts such as homeostasis and regulation. In this context, physiology is uniquely positioned to continue to provide impressive levels of both biological and therapeutic insight by using hypothesis-driven "classical" approaches and concepts to help frame what might be described as the "pieces of the puzzle" that emerge from molecular reductionism. The strength of physiology as a "bridge" between reductionism and epidemiology, along with its unparalleled ability to generate therapeutic insights and opportunities justifies increased attention and emphasis on our discipline into the future. Arguments relevant to this set of assertions are advanced and this paper, which was based on the 2011 Adolph Lecture, represents an effort to fill the intellectual void left by reductionism and improve scientific progress.

homeostasis; regulation; integrative

THIS PAPER REFLECTS IDEAS that were presented as part of the 2011 Adolph Lecture at the Experimental Biology meeting that was held in Washington, DC. The goal of the talk was to share a physiologist's perspective on what reductionism in general and the "omic" revolution in particular has or has not done for biomedical research and associated therapeutic insights or advances. The main ideas highlighted in the lecture were the following.

1) Reductionism via various flavors of molecular biology and "omics" has so far failed to deliver its self-promoted revolution in clinical medicine.

2) Systems biology has a cell-centric focus that is marked by a limited understanding of and application to biology beyond the cell.

3) The failure of systems biology to recognize and use key concepts from physiology about homeostasis, regulation, redundancy, feedback control, and acclimation/adaptation are major limitations to this poorly defined approach.

4) While all the attention has been focused on reductionism and more recently systems biology, physiology continues to provide important biomedical insights that lead to therapeutic advances.

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As the title demonstrates, my goal in the Adolph Lecture and in this paper was and is to be intentionally provocative and hopefully generate a dialogue with the reductionists. In this context, and because I am "taking sides", I have adopted what might be called a conversational approach to this paper.

BIOLOGICAL ORTHOPEDIC SURGERY

A key idea or theme that seems to underpin the impetus for reductionism and various flavors of "omics" as applied to biomedical problems might be described as biological orthopedic surgery: "the gene is broken → fix the broken gene → cure the patient." This thinking clearly seems to explain the enthusiasm about gene therapy that emerged after the discovery of the genetic defect responsible for the most common form of cystic fibrosis and more recently ideas about a limited number of common gene variants explaining the risk for common conditions like atherosclerosis and diabetes (10–12, 43, 51). The line of thinking described above flows from what Denis Noble has critically termed "Neo-Darwinian" thinking about the relationship between genes and phenotype (45, 46). It is exemplified by two quotes, the first from 1989 and second from Francis Collins (the current director of NIH), one of the people involved in the cystic fibrosis gene discovery.

> *The implications of this research are profound; there will be large spin offs in basic biology, especially cell physiology, but the largest impact will be biomedical (51).*

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Here we are in 1997, eight years later, and the management of her disease has not changed. . . . .But I will predict that in the course of the next 10 years management of CF will change. . . . .The healthy form of the gene itself may even be used in so-called gene therapy (12).

What is interesting to note is that while gene therapy for cystic fibrosis has failed to materialize in the 20+ years since the gene defect was identified, there are traditional ion channel-based drugs that target the CFTR protein in clinical trials that show promise in cystic fibrosis (18, 66). At one level, the development of these drugs was likely facilitated by the genetic discoveries because they permitted the development of models that advanced the understanding of the biophysics and ultimately pharmacology of the defective channel. However, one is tempted to speculate, for cystic fibrosis and perhaps other diseases, that much faster therapeutic progress might have been made if traditional physiological and pharmacological approaches had been a bigger area of focus. Perhaps the optimism and drive for gene therapy was an example of what might be termed "silver bullet" thinking that I will discuss below.

REDUCTIONISM IS SEDUCTIVE

The type of reductionism that I have termed "biological orthopedic surgery" has a number of attractive features and is at some level very seductive. It is easy to understand, and when it delivers it is associated with a heroic narrative by a lone scientist or team of scientists making a fundamental discovery that solves a problem. This is the sort of silver bullet thinking mentioned above. However, it has been known for some time that both the easy to understand elements and heroic narratives associated with reductionism are mirages. In this context, when the factors that contribute to biomedical breakthroughs were subjected to analysis by Comroe and Drips (13) in the late 1960s and early 1970s via the "retrospectoscope," biomedical breakthroughs are in fact more nuanced, incremental, and associated with a more serendipitous view of progress vs. the heroic narrative of reductionism.

HEMOGLOBIN IS A SHIFTY MOLECULE

Homeostasis—the ability to regulate key bodily functions within a narrow range in response to either internal (e.g., exercise) or external (e.g., harsh environmental conditions)—is one of the fundamental (perhaps the fundamental) concept in physiology (7). Homeostasis is also subserved by ideas about regulated systems, feedback control, redundant control mechanisms, and adaptation and acclimation over time. These physiological concepts and mechanisms contribute to what might be described as emergent properties, so that the behavior of the system is far more complex and (and likely more robust) than might be predicted on the basis of a single reductionist property (35).

A good, and early, example of this concept comes from the textbook description about the right shift in the oxygen-hemoglobin dissociation curve that occurs at high altitude or during other forms of hypoxia. The standard teaching is that under these conditions there is a rise in 2–3 DPG that allosterically modifies oxygen-hemoglobin dissociation curve and creates a right shift that facilitates the unloading of oxygen at the tissues. However, when measurements of the oxygen-hemoglobin dissociation curve are made in humans who have traveled to high altitude (Fig. 1), under many circumstances there is in fact a net left shift in the oxygen hemoglobin dissociation curve. This left shift is facilitated by the rise in pH and fall in CO_2 caused by the hyperventilation driven by systemic hypoxia. Additionally, under some circumstances, it is driven further leftward by a fall in body temperature (68). Furthermore, it is of interest to note that all genetically adapted high altitude animals and the human fetus in the hypoxic intrauterine environment also have left shifted oxygen-hemoglobin dissociation curves, some with P50 values in the teens.

These observations make it seem likely that the main adaptive strategy is to shift the oxygen-hemoglobin dissociation curve to the left to facilitate the "loading" of oxygen at the lung in conditions (altitude) where oxygen availability is limited. This strategy also takes advantage of the fact that the mitochondria in the tissues can work efficiently at very low P_{O_2} values (and that under specific needs such as muscular exercise in hypoxia local increases in $[H^+]$ and temperature will reduce the leftward shift in muscle capillaries so that "unloading" of oxygen and tissue O_2 levels can be facilitated). It is also of note that the left shift in the oxygen-hemoglobin dissociation curve has been "known" since at least the 1920s. Along these lines, the sequencing of hemoglobin and the understanding of its biophysical properties was one of the earliest triumphs of what has come to be described as molecular biology (55). However, when the interpretation of such discoveries is too narrow, key physiological insights can be missed. The 2–3 DPG story is also an excellent and early example of how physiology trumps reductionist molecular biology as multiple systems and regulatory strategies interact to regulate homeostasis for the whole organism.

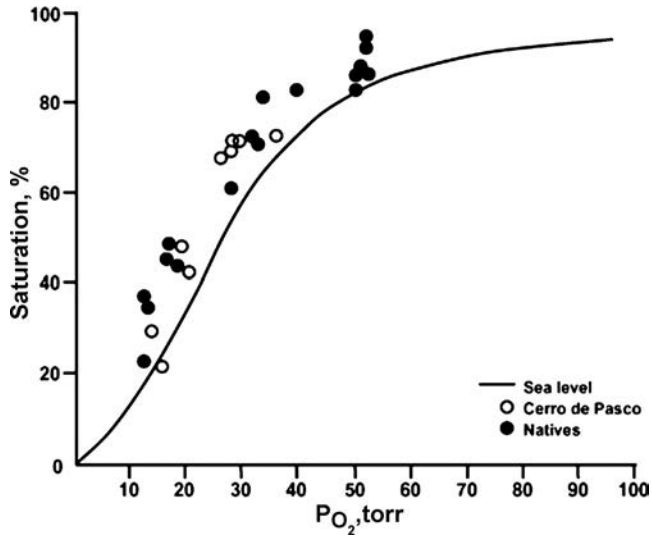

Fig. 1. Oxygen-hemoglobin dissociation curve demonstrating a left shift among sojourners (○) to high altitude and natives. The left shift in the oxygen-hemoglobin dissociation curve under these circumstances demonstrates that the combined effects of hypocapnia, increased pH, and cold override the simple effects of 2–3 DPG on the oxygen-hemoglobin dissociation curve. These data are an outstanding example of the limits of single mechanism reductionism. They are also consistent with the left shift seen in many genetically adapted animals that are native to high altitude. [Reprinted from Ref. 68, with permission from Elsevier.]

PREDICTIVE POWERS OF GENES?

In addition to gene therapy and other molecular treatments for rare diseases, reductionism also made promises about its ability to provide insight about who gets what complex disease like atherosclerosis, diabetes, hypertension, etc. As the quote below demonstrates, this idea became extremely popular after the sequencing of the human genome, and scientific funding agencies like the National Institutes of Health have invested huge sums of money in so-called "genome wide association studies" (GWAS) and other efforts to determine if a few genetic variants are harbingers of future disease in the population as a whole (10, 12, 43).

> *. . . because it been known all along that virtually every disease tends to track in families. What has changed is that. . . . .we are now beginning to see possible therapeutic approaches based on gene discoveries that will change the way medicine is practiced (12).*

One attractive element of this paradigm was that if a few common variants explained much of the risk for disease like diabetes, then it should be possible to identify those at risk and target them for early intervention. So far, the data from many, if not most or even all of these studies, have been underwhelming (43). First, a large number of variants seem to cause a significant increase in risk, but this increase is small compared with behavioral and environmental factors. An increased risk of several percent seems also likely to fall below what might be described as a phenotypic signal-to-noise ratio. Second, when the gene variants (single nucleotide polymorphisms, SNPs) that have been identified via GWAS or other experimental approaches are tested in large populations, the distribution of risk SNPs is typically strikingly similar in populations with and without disease (50, 63; Fig. 2). Third, when so-called genetic risk scores for disease are compared with predictive algorithms based on traditional risk factors (family history, lifestyle, age, etc.), the genetic risk scores are far less predictive than traditional phenotype-based risk scores. Furthermore, addition of genetic risk elements to phenotypically based scores adds little or no additional predictive power (50, 63). Finally, the idea that identifying prospective genetic risks for complex diseases that include a number of lifestyle and environmental factors (and increasingly even prenatal factors) is fundamentally wishful thinking, because behavioral health issues and culture play such a dominant role in determining who gets what disease when, and it is unclear if people will change their behavior in a positive way if they know prospectively they are at increased risk (24). Paradoxically, perhaps those at reduced genetic risk would pay less attention to behavioral risks.

SUCCESS IN PHARMACOGENOMICS AND ANTHROPOLOGY

So far, this paper has offered a sharp critique of the reductionists and taken the position that they over-sold what their technology had to offer on both the individual (gene therapy) basis and also in terms of population risk and intervention. However, there have been some notable successes stemming from application of this technology and two that seem especially worthy of comment. For example, there has been success in so-called pharmacogenomics. It has been well-known for some time that there are "responders" and "non-responders" to many forms of drug therapy. In many cases, this is related to how rapidly drugs are metabolized. In the case of tamoxifen, which had a dramatic effect on the recurrence of breast cancer, individuals with decreased drug metabolism appear to be at increased risk for recurrence. This is especially important for drugs like tamoxifen, which are ingested as pro-drugs with one or more metabolites that are active (56).

Another field where "omic" approaches have yielded dividends is anthropology. Two good examples include discoveries related to the independent development of lactase persistence into adulthood in areas of the world that were early adopters of herding (23, 34). In this context, one can imagine that the ability to digest lactose into adulthood provided the affected individuals a significant survival advantage and thus became the dominant genotype in only a few generations. Another good example that is perhaps counterintuitive relates to the individuals who migrated to the Tibetan plateau. These individuals do not develop chronic mountain sickness even with lifelong living at 3–4,000 m of elevation. These responses contrast to the high altitude natives in the Andes Mountains, who do develop chronic mountain sickness (58, 61, 70). Along these lines, those who migrated to the Tibetan plateau appear to have had selection pressure that favored a less functional variant of the hypoxia-inducible factor that, among other things, prevents them from developing excessive polycythemia, which plays a critical role in chronic mountain sickness.

INTERIM SUMMARY

So far, I have provided a general critique of what might broadly be termed "molecular reductionism". I have presented evidence that its failure to live up to its self-generated hype is in reality a failure to recognize larger ideas about homeostasis

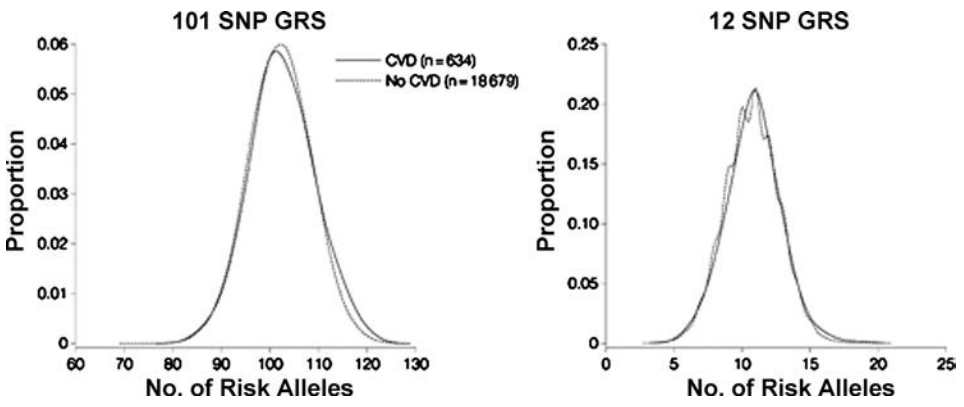

Fig. 2. Distribution of so-called high risk genes for cardiovascular disease in women with and without known coronary artery disease. The distribution of risk genes is similar, and construction of a genetic risk score for cardiovascular disease is thus problematic. This is just one example of the limited predictive power of "genomics" as it relates to the ability of relatively common gene variants to predict common diseases. [Borrowed with permission from Ref. 50. Copyright © 2010 American Medical Association. All rights reserved.]

and regulation that are central to physiology. This includes the specific example of the idea of gene therapy for relatively common genetic disorders like cystic fibrosis and also the limited predictive power of gene variants for common diseases. The question now is whether there is some way out of this problem and a better way to use potentially powerful technologies championed by the reductionists in a biomedical context.

IS SYSTEMS BIOLOGY THE ANSWER?

One idea to address the "failure" of molecular reductionism described above is to use a new approach called systems biology. The idea is that if powerful modeling tools and other data analysis techniques could be applied to the data generated via high throughput molecular reductionism, then somehow more meaningful insights would be generated and ultimately exploited for predictive or therapeutic purposes. The rationale for systems biology comes from a sampling of the comments on www.systemsbiology.org web site (34a).

> *Systems biology is the study of an organism, viewed as an integrated and interacting network of genes, proteins and biochemical reactions which give rise to life. Instead of analyzing individual components or aspects of the organism, such as sugar metabolism or a cell nucleus, systems biologists focus on all the components and the interactions among them, all as part of one system. These interactions are ultimately responsible for an organism's form and functions.*
>
> *Traditional biology—the kind most of us studied in high school and college, and that many generations of scientists before us have pursued—has focused on identifying individual genes, proteins and cells, and studying their specific functions. But that kind of biology can yield relatively limited insights about the human body.*
>
> *Biologists, geneticists, and doctors have had limited success in curing complex diseases such as . . . . diabetes because traditional biology generally looks at only a few aspects of an organism at a time.*

To a physiologist, there are obvious problems with systems biology. The problems start with the fact that physiology has been attempting for hundreds of years to understand the integrated function of organs and whole organisms that culminated in unifying big ideas about homeostasis and regulation discussed earlier. It is also clear that the type of biology that physiologists have been interested in starting with Harvey and the circulation has been about systems and has used modeling and computational techniques (1, 32, 57). Additionally, at this time the concept of systems biology and how it is defined remains very nebulous (52). Is systems biology a new discipline, an approach, a collection of tools, or merely a new name for integrative physiology generated by individuals who are generally unaware that our field exists (2, 28, 34a, 36, 40, 41, 45, 57)? Clearly physiology has provided and continues to provide insight about human disease, including insight that has led to vast therapeutic advances in recent years (37). Perhaps, the obvious question for the advocates of the cell-centric view of systems biology is did they skip physiology as part of their course work as students?

The concerns about systems biology outlined above at some level are about definitions and perhaps intellectual ownership. However, it also seems fair to ask what the long-term outlook for cell-centric systems biology is as an approach to making sense out of the vast amounts of data that can be generated using modern "omic" technology. In this context, there are key intellectual issues related to how data elements are generated, their spatial and temporal relationships, and how many ways they might interact (Fig. 3) that question the very fundamental assumptions about systems biology and its reliance on "bottom up" or "hypothesis neutral" modeling (2, 6, 15, 27, 35, 36, 38, 48, 67). It seems to me that without a narrative approach that includes hypothesis testing and key concepts like homeostasis, systems biology runs the risk of becoming scientific "Abstract Expressionism". Given the issues discussed earlier with gene therapy and GWAS approaches and the hype that surrounds systems biology, these concerns raise questions about what kind of science and scientific approaches deserve our future attention and funding (2, 24, 35).

REDUCTIONISM STALLS PHYSIOLOGY PROGRESSES

This is not the place for a comprehensive review of the contributions of physiology to biomedical research and therapeutic progress over the last 20–30 years. However, a few highlights that were initially seen as counterintuitive seem warranted. An obvious one is the discovery of EDRF and nitric oxide (25). This observation, which challenged the idea of the endothelium as merely a barrier, led to the discovery of gas-based signaling mechanisms and new therapeutic targets for conditions as diverse as erectile dysfunction and pulmonary hypertension. Would gas-based signaling mechanisms have been discovered by sequencing genes? Physiology has also helped redefine the optimal strategy used during mechanical ventilation in patients with adult respiratory distress syndrome (ARDS; 26). This has led to abandonment of strategies associated with high airway pressures and maintenance of arterial blood gases toward so-called permissive hypercapnia, alternate forms of mechanical ventilation and pressure support. Importantly, these new strategies that emphasize the avoidance of barotrauma have been associated with significant reductions in morbidity and mortality for ARDS. While part of the conventional wisdom now, this strategy was initially seen as counterintuitive.

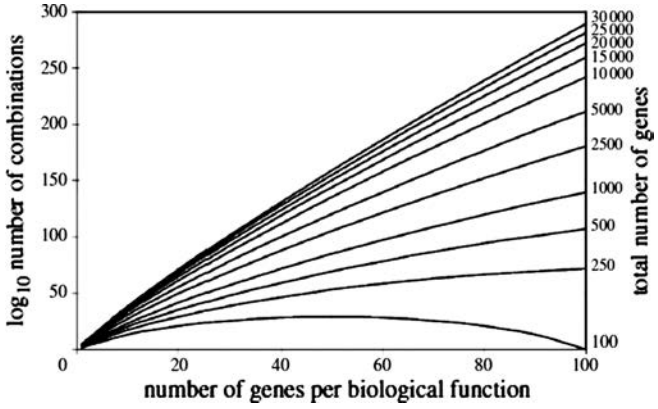

Fig. 3. Simulation of a number of possible combinations of genes gene interactions depending on the number of genes per biological function (*x*-axis) and the total number of genes in the organism. For biological functions with roughly 50 genes, $\sim 10^{150}$ possible combinations exist for most mammals. This figure shows the immense challenge associated with hypothesis-neutral systems biology and "bottom up" modeling. [Borrowed with permission from Ref. 46.]

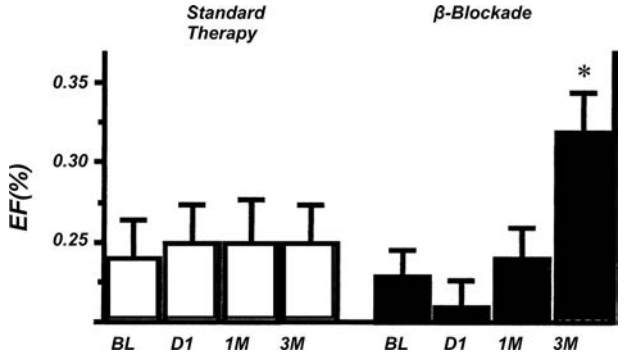

Fig. 4. Demonstration that beta-blockade can improve ventricular function (%EF) in humans with congestive heart failure over time. Standard therapy was associated with stable ventricular ejection fraction over 3 mo. By contrast, metoprolol (β-blockade) increased ventricular ejection fraction by >50% over 3 mo (*<0.05 vs. baseline). This finding, while initially counterintuitive, was based on sound physiological reasoning and along with other therapies has improved outcomes for patients with congestive heart failure. [Adapted from Ref. 20, with permission from Wolters Kluwer Health.]

Another example of a counterintuitive physiologically based clinical strategy was the use of beta-blockers in congestive heart failure. For many years these drugs were contraindicated in congestive heart failure (CHF) because it was felt that high sympathetic drive to the heart was required to maintain an adequate cardiac output in CHF. In reality, high sympathetic activity to the heart over time contributed to the progression of the disease and promoted a downward spiral of cardiac remodeling and reduced function (20). Thus the use of beta-blockers along with vasodilator therapy has been revolutionary and can interrupt or slow the downward spiral noted above in patients with congestive heart failure (Fig. 4). Again, the conventional wisdom was turned on its head and provided new insights that ultimately led to improved therapy. In the case of ARDS and congestive heart failure there has also been a two-way street between observations from clinical research conducted "at the bedside" to more fundamental observations in the laboratory.

Three other examples of more straight forward physiologically based therapeutic successes in recent years include the long story of improved outcomes for premature infants cared for in the neonatal ICU including altered ventilatory strategies, avoidance of oxygen toxicity, and surfactant therapy (9, 60). These improved outcomes, in the littlest ICU survivors, continue to seem miraculous to individuals who care for these patients and practiced medicine or nursing prior to their use. A second example has been oral rehydration solutions that are life saving in infants and children with diarrheal disease, especially in developing countries where it is a primary and frequent cause of death (8). Finally, in the developed world, where obesity and physical inactivity are leading to a pandemic of type 2 diabetes, physical activity (especially walking training in middle-aged people) has been proven to be highly effective in preventing, limiting, and in some cases reversing type 2 diabetes (16, 29). Each of these therapeutic successes is based on a foundation of physiologically based experimental evidence and insights.

REDUNDANCY, FEEDBACK, AND ACCLIMATION/ADAPTATION

Why has physiology continued to contribute in the era of reductionism? Physiologists are well versed in the overall concept of homeostasis, regulation, feedback, redundancy, and acclimation/adaptation. A classic example of redundancy comes from coronary circulation where coronary vasodilation is tightly linked to myocardial oxygen demand. In this context, a number of vasodilator systems likely contribute to this response. However, pharmacological blockade of one system, or in fact multiple systems, fails to alter this fundamental relationship between coronary vasodilation and myocardial oxygen demand in most species (19, 64; Fig. 5) This suggests that multiple redundant pathways contribute to this critical physiological response so that when one is blocked or absent, oxygen supply to the heart is not threatened when demand rises.

The fundamental relationship between coronary vasodilation and myocardial oxygen demand is also an observation that has had vast therapeutic implications and explains in large part why age specific death rates for cardiovascular disease have fallen dramatically over the last 30–40 years. There are drugs the reduce myocardial oxygen demand, mechanical therapy like stents, bypass surgery that improves myocardial oxygen delivery, and other drugs and lifestyle interventions that can affect both elements of the equation over time (30, 44). This physiological narrative and the progress that has flowed from it is in stark contrast to the relative lack of progress against cancer where there does not seem to be a unifying physiologically based story or model that can be exploited to address the general problem of cancer.

One of the classic feedback control mechanisms in physiology is the arterial baroreflex. While barodenervated animals have relatively normal blood pressure over a given 24 h period, their blood pressure becomes much more variable (14). The relative stability of blood pressure in the long run shows the power of redundant control via renal regulation of arterial pressure. However, for short-term adaptations, essential for things like exercise or changes in posture, feedback control

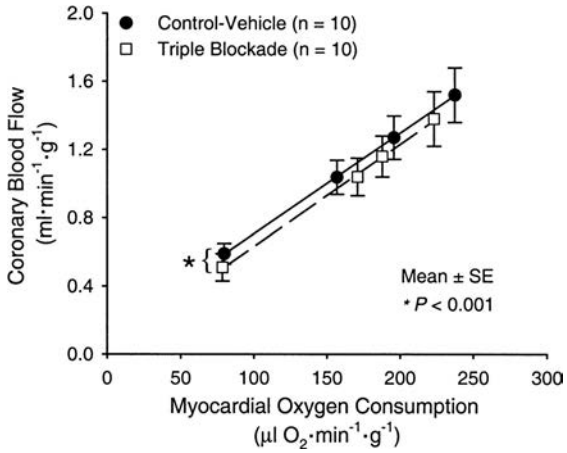

Fig. 5. Myocardial oxygen demand on the x-axis and coronary blood flow on the y-axis. Note that coronary blood flow rises in proportion to myocardial oxygen demand and that this rise is unaffected by triple inhibition of kATP+ channels, nitric oxide synthase, and adenosine receptor s This is a classic example of the concept of physiological redundancy. This well-known phenomenon may also explain why the absence of many so-called critical genes or proteins has limited impact on overall organ or organism function. This is because so-called redundant systems are able to alter their function and "upregulate" when one or more systems is blocked. [Borrowed with permission from Ref. 64.]

from arterial baroreflexes is essential for normal physiological responses.

An outstanding example of how humans acclimatize and adapt to physiological stress comes from studies that demonstrate that the ability of individuals to exercise in the heat can be remarkably improved by a few weeks of training in the heat (54). This improved exercise tolerance in the heat is associated with expanded plasma volume, increased sweating, and altered thermoregulatory skin blood flow. Another outstanding example is what might be called the adaptability of insulin sensitivity and glucose uptake in skeletal muscle. These variables are extremely sensitive to exercise and changes in daily activity and seem especially relevant in the era of the physical inactivity/obesity pandemic (29, 49, 53, 65).

Ideas about redundancy, feedback control, and acclimation/adaptation are also why physiologists are not that surprised by the ability of various gene knockout animals to survive and thrive (33). At some level this approach is conceptually similar to the classic denervation or high dose pharmacological blockade studies used by physiologists for generations and primarily show the power of the regulatory mechanisms highlighted above to preserve both long term phenotype and homeostasis despite the loss of one or more critical pathways or mechanisms (17). In this context, it is not surprising the yeast can survive without 80% of their genes and the function of these genes only becomes apparent when the organism is stressed (33). Is it too cynical to point out that knockout animals are essentially a "can't lose" experimental approach? If the knockout is lethal or leads to significant phenotypic dysfunction it is essential. If it survives then genetic or other compensatory mechanisms were upregulated to overcome the absence of the essential gene.

Physiology or physiologically based tests can also provide insight into the risk of future disease and/or predictive outcomes. For example, the blood pressure responses to common sympathoexcitatory stress can be used to define those at risk for future hypertension in a way that is potentially much more predictive than any current genetic test. Additionally, tests of autonomic function are strong predictors of outcomes in large populations of humans, and cardiorespiratory fitness is an especially good predictor of all-cause mortality.

TOOLS VS. BIG IDEAS

At some level molecular reductionism and systems biology are at existential cross roads. Are they in fact real disciplines informed by big ideas like homeostasis and regulation, or are they essentially tools and approaches that will facilitate the work of disciplines informed by bigger ideas and more importantly bigger questions and more comprehensive strategies? Based on the concepts and examples highlighted in this paper I would argue that until the vast amounts of data generated by modern "omic" techniques are put in a physiological context it will be an exercise in what Sydney Brenner has deemed "low input, high throughput, no output biology" (6). Along these lines, I want to end on an optimistic note with examples of how physiology is making a difference by applying reductionist tools as part of a more comprehensive approach to important questions. Because the Adolph lecture is sponsored by the Exercise and Environmental Physiology section of the American Physiological Society, relevant examples from related areas will be used. In each case there seems to be an overall hypothesis and a strategy that exploits what might be called responders and non-responders to an intervention.

Britton and Koch and colleagues (39, 69) have used selective breeding strategies to develop rats with vastly different inherent aerobic endurance capacities (Fig. 6). These animals have been used in a variety of studies to better understand the gene environment interactions. In many instances the animals selected for low intrinsic aerobic capacity seem to be at increased risk for complex diseases like diabetes, obesity, and heart disease. Additionally, studies using these animals have begun to identify genetic and transcriptional factors and networks that explain in part this increased risk (39).

Another example of how physiologists are using tools from the "new biology" is the HERITAGE study, which broadly seeks to understand the genetic basis for the differing physiological responses to exercise training in a large number of humans exposed to a standard protocol (3–5). This is an excellent example of how what might be called "high resolution" physiologically based phenotyping in conjunction with genetics. This hypothesis-driven approach also includes uses

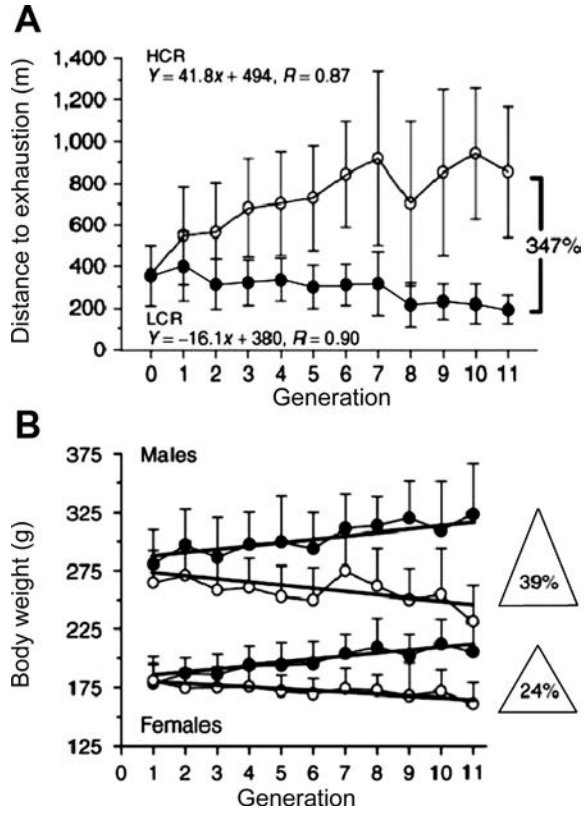

Fig. 6. Selective breeding of rats with divergent aerobic capacities. These data show that animals selected for their running capacity diverge dramatically after a few generations and is sustained for many generations. Importantly, at the same time body weight also began to diverge as did a number of risk factors for cardiometabolic disease. Phenotypic studies conducted on these animals in conjunction with more targeted forms of "omic" approaches and other types of molecular reductionism are providing new insights about gene environment interactions. These findings may also have applicability to physically active and inactive humans. The approach of Britton and Koch is a classic example of using reductionist tools in a physiological context to gain new insights with direct applicability to human health and disease. [Reprinted from Ref. 39 with permission from Macmillan Publishers Ltd. *Obesity Suppl*. copyright 2008.]

various "omic" and systems biology approaches and was initiated by physiologists before the terms genomics or systems biology existed. Additionally, like the examples from pharmacogenomics and anthropology discussed earlier, it takes advantage of the fact that there are responders and non-responders in response to a given intervention or environmental stressor.

Finally, my collaborator John Eisenach and I along with our colleagues have performed carefully controlled studies on how common genetic variants in the β_2-adrenergic receptor influence a number of physiological responses and how any genotype-based differences might be influenced by dietary sodium (21, 22, 31, 59). These studies were initiated because epidemiological evidence suggested that genetic variation in the β_2-adrenergic receptor influenced blood pressure in large populations. In our studies only homozygotes for the genetic variant of interest were recruited in an effort to see the maximum potential physiological effect of the variants. Using this approach, it appears that there are genotype-specific patterns associated with increased cardiac output responses to exercise that may interact with NO-mediated β_2-adrenergic receptor peripheral vasodilation. These responses clearly link and mechanistically define how a common gene variant in a key regulatory system can influence a physiological response in humans. They may also provide physiological explanations relevant to the original epidemiological observations on blood pressure and other outcomes, including those in patients with the acute coronary syndrome (42).

SUMMARY

In this paper and in the Adolph Lecture I have highlighted some of the claims associated with molecular reductionism and more recently systems biology. In both cases I have argued that the apparent inability and/or unwillingness of the advocates of these approaches to use key concepts from physiology and ultimately use their tools in a physiological context has limited the contribution of the approaches they advocate. By contrast physiology has continued to use new tools in the service of its big ideas and also continued to provide biomedical insight and therapeutic advances. As the final examples show, it is possible to incorporate reductionist tools in a physiological context to gain broader biomedical insights. Hopefully these insights will fuel the next wave of physiologically inspired therapeutic advances.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author.

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RESEARCH ARTICLE

Robustness and timing of cellular differentiation through population-based symmetry breaking

Angel Stanoev*, Christian Schröter and Aneta Koseska‡,§

ABSTRACT

During mammalian development and homeostasis, cells often transition from a multilineage primed state to one of several differentiated cell types that are marked by the expression of mutually exclusive genetic markers. These observations have been classically explained by single-cell multistability as the dynamical basis of differentiation, where robust cell-type proportioning relies on pre-existing cell-to-cell differences. We propose a conceptually different dynamical mechanism in which cell types emerge and are maintained collectively by cell-cell communication as a novel inhomogeneous state of the coupled system. Differentiation can be triggered by cell number increase as the population grows in size, through organisation of the initial homogeneous population before the symmetry-breaking bifurcation point. Robust proportioning and reliable recovery of the differentiated cell types following a perturbation is an inherent feature of the inhomogeneous state that is collectively maintained. This dynamical mechanism is valid for systems with steady-state or oscillatory single-cell dynamics. Therefore, our results suggest that timing and subsequent differentiation in robust cell-type proportions can emerge from the cooperative behaviour of growing cell populations during development.

KEY WORDS: Symmetry breaking, Differentiation, Cell-cell communication, Inhomogeneous steady state

INTRODUCTION

Functional diversification of cell types during mammalian development is characterised by the transition from an initially homogeneous group of multilineage primed cells towards a heterogeneous population of differentiated cell types (Zhang and Hiiragi, 2018; Simon et al., 2018). To ensure robust development, the onset of the differentiation event must be accurately timed, and the number distribution of each cell type must be correctly established.

The experimental observation that the expression of mutually exclusive genetic markers distinguishes the differentiated cell types from each other, and from the multilineage primed state, has promoted the hypothesis that cell types correspond to one of multiple stable gene expression states that arise from intracellular gene regulatory networks. Switching between these distinct states that dynamically represent stable attractors, specifically from the attractor encoding the multilineage primed state to the differentiated states, has been assumed as the dynamical basis of differentiation (Kauffman, 1969; Andrecut et al., 2011; Wang et al., 2011; Enver et al., 2009). The most common motif that accounts for bistability, i.e. the co-existence of two stable gene expression patterns on a single-cell level, is a two-component toggle-switch gene network (Thomas, 1981; Cherry and Adler, 2000; Snoussi, 1998). The addition of self-activating loops to each of the toggle-switch genes gives rise to a third stable state through which the multilineage primed co-expression state has been typically explained (Huang et al., 2007; Bessonnard et al., 2014; Jia et al., 2017). Such single-cell multistable circuits have been used to describe, for example, the Cdx2-Oct4 (also known as Pou5f1) switch in the differentiation of totipotent cells of the early embryo (Niwa et al., 2005), as well as the Gata6-Nanog switch in the differentiation of cells in the inner cell mass (Bessonnard et al., 2014; Chickarmane and Peterson, 2008; Schröter et al., 2015). The differentiation outcomes have thereby been typically analysed from a single-cell perspective, assuming that the intrinsic transitions towards one of the co-existing stable states are either driven stochastically (Gupta et al., 2011), modulated by an external signalling input, or stemming from cell-to-cell heterogeneity (De Mot et al., 2016; De Caluwé et al., 2019). However, the respective cell-type proportions strongly depend not only on the parameters of the system but also the initial conditions, indicating that the underlying mechanism of reliable proportioning cannot be directly inferred from this view.

On the other hand, experimental evidence suggests that paracrine signals have a crucial role for reliable cell-type establishment (Monk, 1997; Nichols et al., 2009; Yamanaka et al., 2010; Youk and Lim, 2014; Hart et al., 2014; Saiz et al., 2020). This has been particularly recognised in lateral inhibition models, such as the Delta-Notch system (Sprinzak et al., 2010; Collier et al., 1996), in which the intercellular communication realised through toggle switches distributed between the cells enables differentiation into distinct cell types with specific proportions and spatial organisation (Collier et al., 1996; Formosa-Jordan and Ibañes, 2014; Teomy et al., 2019 preprint; O'Dea and King, 2012). A similar model relying on cell-cell communication via fibroblast growth factors has been recently proposed for the cell-type specification in the mouse blastocyst (Saiz et al., 2020).

The emergence of specific gene expression profiles due to cell-cell communication is also well exemplified by the quorum-sensing mechanism in bacteria, in which the timing of emergence is regulated through the concentration of secreted signalling molecules (Taga and Bassler, 2003; You et al., 2004; Danino et al., 2010). Thus, these examples indicate that novel attractors can emerge in populations of communicating cells that are not present for isolated cells. This principle of attractor emergence in coupled systems has been extensively investigated in both natural and synthetic genetic networks (McMillen et al., 2002; Taga and Bassler, 2003; Kuznetsov et al., 2004; Garcia-Ojalvo et al., 2004; Ullner et al.,

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2007). For example, emergent oscillatory solutions (Ullner et al., 2007, 2008; Koseska et al., 2010) have been proposed as dynamical mechanisms of stem cell differentiation with self-renewal (Suzuki et al., 2011). These theoretical and experimental findings suggest that cooperative dynamics could underlie the emergence of differentiated cell types in cell populations. However, the principles that govern self-organised differentiation timing, while at the same time leading to specific cell-type proportions that can reliably adapt upon perturbations, remain unresolved.

We propose a dynamical mechanism that underlies the differentiation of cell populations into cell types with stable proportions driven by the growth of the communicating population itself. Within this model, the expression profiles of both the multilineage primed and the differentiated cell types can be captured without any change in the parameters, and the transition between them can be established at a specific size of the population. The same mechanism also enables robust recovery of the acquired proportions upon perturbation of the system, accounting for autonomous scaling. We show that these properties of a communication-based cellular system arise from a collective symmetry breaking through a subcritical pitchfork bifurcation (PB). Dynamically, this novel collective state of mutually exclusive gene expression states in the population is represented as a single inhomogeneous steady state (IHSS). This renders the individual differentiated cell types dependent on each other, and the respective gene expression profiles different from those that can be attained in isolated cells. We show that the differentiation timing occurs through the growth of the population beyond a critical size, when the parameters of the undifferentiated cell population correspond to organisation before the PB. These findings indicate that the proposed collective inhomogeneous solution is a generic dynamical mechanism that describes how heterogeneous cellular types emerge from a homogeneous population of precursor cells and are maintained via cell-cell communication.

RESULTS

Timing and stable proportions of differentiated cell types are generated in growing populations

Cell differentiation during early mammalian embryogenesis often occurs from a multilineage primed state (*mlp*), which is maintained for several cell division cycles before differentiation into distinct cell types occurs (Fig. 1A) (Saiz et al., 2016; Hatakeyama et al., 2004; Soldatov et al., 2019). This implies that gene expression states transit from an initial homogeneous pattern across the precursor cells towards a heterogeneous expression state representing the differentiated cell types.

To investigate under which conditions such transition occurs, we considered a generic cell-cell communication system, in which the gene regulatory circuits in single cells are coupled to each other by paracrine signalling molecules s (Fig. 1B). The intracellular circuit consists of two genes u and v that inhibit the transcription of each other, and u additionally positively regulates the secretion of s. In turn, the extracellular concentration of the signalling molecules, s_{ext}, regulates the circuit dynamics (inhibiting u production; Fig. 1B). As the communicating signals are secreted by the cells themselves, their concentration is a variable in the system. This effectively

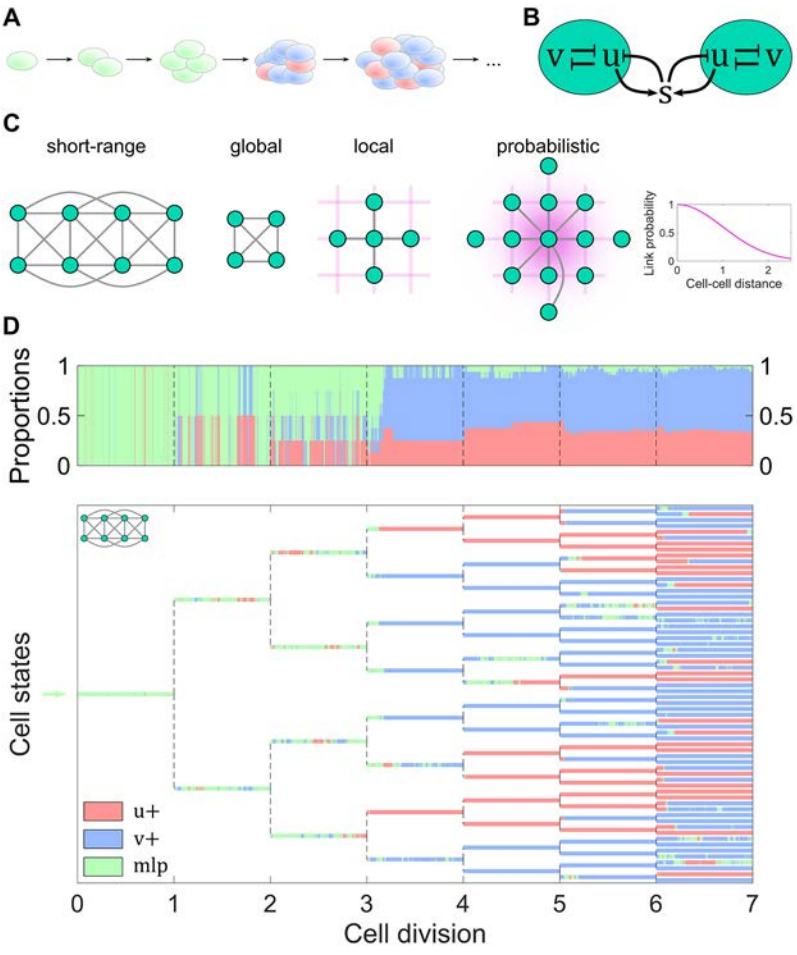

Fig. 1. Emergence of stable proportions of differentiated cell types in growing cell populations. (A) Schematic of the transition from multilineage primed cell types towards differentiated cell types during early embryogenesis. (B) Network topology of the cell-cell communication system (Eqn 1). (C) Different communication scenarios on a grid: short-range, global, local and distance-based probabilistic coupling. (D) Lineage tree depicting the transition from a multilineage primed state (*mlp*) to the *u*+/*v*+ states in a growing population with short-range communication, determined from a stochastic simulation. Green/red/blue: *mlp*/*u*+/*v*+ cells, respectively. Top: respective cell-type proportions. Parameters: α_u=2.3, α_v=3.5, α_s=2, $\alpha_{u,s}$=1, β=γ=δ=η=2 and λ=50.

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establishes a single joint dynamical system that is described by the following dimensionless equations:

$$\begin{aligned}\frac{1}{\lambda}\frac{\mathrm{d}u_i}{\mathrm{d}t} &= \alpha_u \frac{1}{1+v_i^{\beta}} + \alpha_{u,s}\frac{1}{1+s_{i,ext}^{\eta}} - u_i \\ \frac{1}{\lambda}\frac{\mathrm{d}v_i}{\mathrm{d}t} &= \alpha_v \frac{1}{1+u_i^{\gamma}} - v_i \\ \frac{1}{\lambda}\frac{\mathrm{d}s_i}{\mathrm{d}t} &= \alpha_s \frac{u_i^{\delta}}{1+u_i^{\delta}} - s_i,\end{aligned} \tag{1}$$

where $i = \overline{1,N}$ is the single cell index and N is the number of cells. The vector (u_i, v_i, s_i) represents the state of each cell within the $3N$-dimensional state of the coupled system $(u_1, v_1, s_1, \ldots, u_N, v_N, s_N)$. The external amount of signal perceived by cell i from its communicating neighbourhood $N(i)$ (including itself) is defined as $s_{i,ext} = (1/(|N(i)|+1))\sum_{j\in(N(i)\cup i)} s_j$, i.e. the average amount of secreted signalling molecule at the given time. The parameters α_u, α_v, $\alpha_{u,s}$ and α_s represent the respective promoter strengths, whereas β, γ, η and δ are the Hill coefficients. Aiming to conceptualise the problem rather than to provide a quantitative description, the system was scaled to yield a minimal number of parameters: rate constants proportional to the promoter strengths were on the same order of magnitude, and the Hill coefficients were set to 2 (Materials and Methods).

Employing this model, we generated a numerical lineage tree starting from one cell, using stochastic simulations. The population growth was implemented in a simplified manner: after a given time period that mimics cell cycle length, all cells divide and the number of cells is doubled. The initial gene expression states of the daughter cells are inherited from the final state of the mother cell. The cells are placed on a grid with no flux boundary conditions, and the communication between them is short-ranged (within distance 2), i.e. between adjacent and second-adjacent cells on the grid (depicted for N=8 cells in Fig. 1C, left). Although we mainly focus on this communication type, the effect of other coupling types is also explored further below: global all-to-all, local (only between adjacent cell) and distance-based probabilistic coupling, in which interaction links between cells are established with decreasing probability as the distance between them increases (Fig. 1C). Cell divisions occur along the horizontal and vertical axes of the grid alternately, such that the grid doubles in size after each division event, yielding lattices of 1×1, 1×2, 2×2, 2×4, etc. (Fig. S1). The collective system state constituted of u+, v+ or *mlp* cell types was characterised in every time instance by categorising the cell states, and was used to plot the temporal evolution of the lineage tree (Fig. 1D). Furthermore, cellular proportions in the system were estimated from the collective state at each time point, and their temporal evolution is shown in the panel above the lineage tree.

The simulations demonstrated that even in the presence of gene expression noise (σ=0.1, Materials and Methods), for a population size of up to N=4 cells, the dynamical state of the system was homogeneous such that individual cells had equivalent u/v co-expression patterns resembling an *mlp* state (Fig. 1D). However, when the population reached a threshold size of N=8 cells, the expression patterns in single cells collectively transitioned to u- or v-dominated expression (u+ or v+ cells), indicating that the initial symmetry of the system had been broken and cells differentiated. Interestingly, defined proportions of u+ and v+ cells emerged upon differentiation, which were stably maintained over many rounds of cell division (Fig. 1D, top).

That the *mlp* state could be maintained for smaller population sizes, despite the presence of gene expression noise, indicates that stochastic events do not trigger the transition from a homogeneous to a heterogeneous cell population. As the model parameters also do not change, these results rather suggest that the timing of the transition event emerges from the growth of the population, upon which distinct proportions of the generated heterogeneous cell types are established.

Collective state with heterogeneous cell types emerges with precise timing due to subcritical organisation

To uncover the dynamical mechanism that underlies the transition between the *mlp* and the u+/v+ cell types, we performed a bifurcation analysis. The results in Fig. 1D indicated that differentiated cell types emerge with growing population size. However, a direct identification of the transition type using the number of cells as a bifurcation parameter cannot be performed, as it is not an explicit parameter in the model (Eqn 1). As a first step, we therefore chose α_u as a representative bifurcation parameter to identify and characterise the solutions of the system, whereas the impact of population size will be explored further below.

The bifurcation analysis showed that for N=2 coupled cells, the system exhibits qualitatively different dynamics for different α_u values. For lower α_u values, the system exhibits monostable behaviour (Fig. 2A, top, green circle for α_u=2.3). Here, both cells populate the same state (u_1=u_2) as evident from the projection that falls on the diagonal in the u_1–u_2 state space (Fig. 2A, bottom left). This homogeneous steady state (HSS) captures the *mlp* state with a characteristic precursor u/v co-expression pattern. On the level of a single-cell system, this is the only stable regime over the full α_u domain (Fig. S2A), meaning that isolated cells will maintain the *mlp* state.

However, at a critical α_u value, the symmetry of the *mlp* HSS is broken via a subcritical PB. From the point of view of dynamical systems, the HSS (Fig. 2A, black line) loses its stability at this parameter value and a pair of fixed points is generated, giving rise to IHSSs stabilised via saddle-node bifurcations (SN) (Fig. 2A, purple lines). There is a co-existence between the HSS and the IHSS before the PB, rendering it subcritical. The IHSS is a single attractor, here a six-dimensional point (u_1, v_1, s_1, u_2, v_2, s_2), that describes a heterogeneous state. This state consists of a high u-expression level (u+) in one cell (u_2) and a low u-expression level (v+) in the other cell (u_1), as shown by the two-dimensional (u_1, u_2) projection (Fig. 2A, bottom right). This means that the IHSS is a symmetry-broken collective state (Koseska et al., 2013), as it describes simultaneously both cell types with mutually exclusive gene expression patterns (Fig. S2B,C). As there is no preference which cell will acquire the u+ or v+ cell type, both possibilities (u_1<u_2 and u_1>u_2) are present as branches (upper and lower branch in Fig. 2A, top, respectively). Therefore, the same fixed point will be manifested as an upper branch for the u+ cell, but as a lower branch within the equivalent bifurcation diagram for the v+ cell. The u_1–u_2 state space projection also demonstrates that the IHSS solutions are reflections of one another over the diagonal (Fig. 2A, bottom right). This demonstrates that PB provides a unique mechanism for a dynamical transition from a homogeneous (*mlp*, HSS) to a single but heterogeneous (u+/v+, IHSS) state of the population, in which the differentiated cell types always jointly emerge. The described IHSS solution of a coupled system is fundamentally distinct from a bistable system on a single-cell level. There, the u+ and v+ cell types are described by two different steady states. Thus, in the absence of cell-cell communication, each cell in a population can independently transition to one of them.

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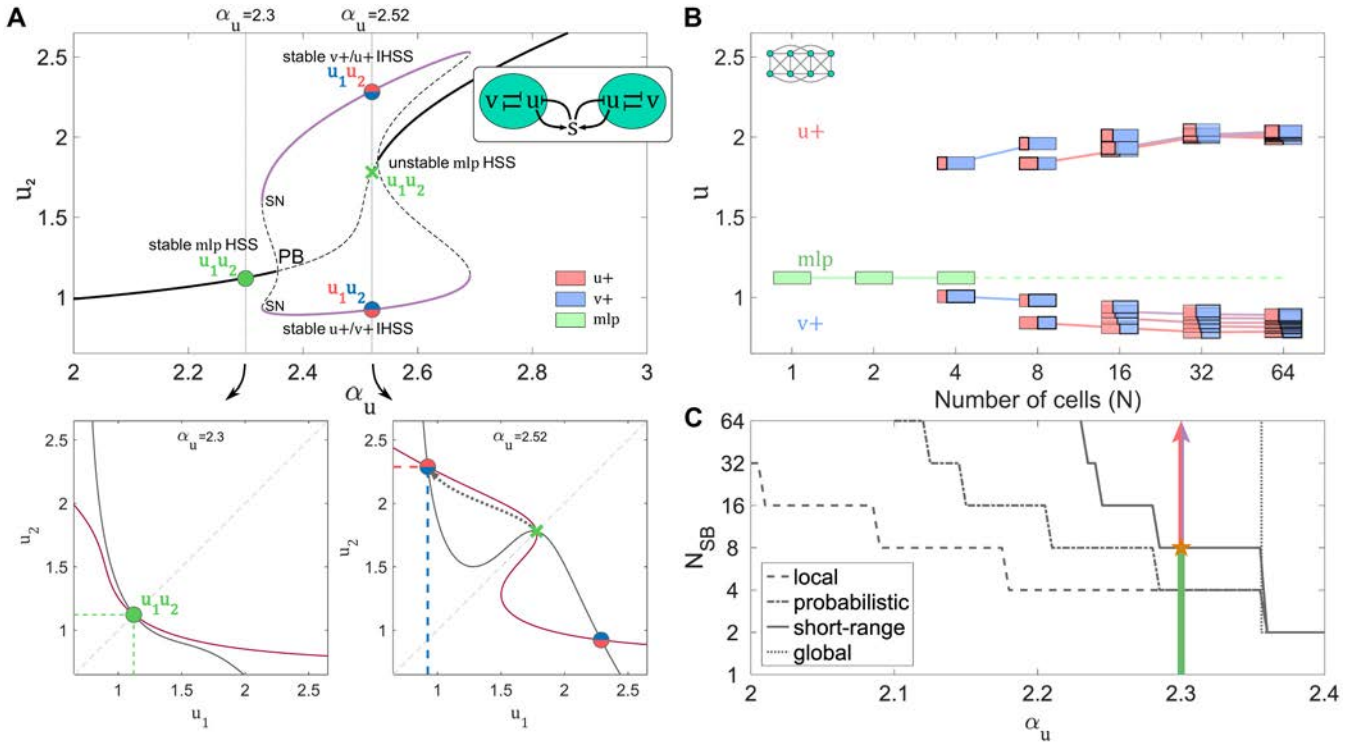

Fig. 2. Subcritical organisation before the PB enables timing of cellular differentiation. (A) Top: bifurcation diagram for N=2 coupled identical cells (inset), using u_2 as a representative variable. Solid lines indicate HSS (black) and IHSS (purple). Dashed lines indicate unstable steady states. Dotted lines indicate organisations in parameter space, with corresponding stable *mlp* HSS (solid green circle, α_u=2.3), *u*+/*v*+ IHSS (solid red/blue circles, α_u=2.52) and unstable HSS (green cross, α_u=2.52). Bottom: corresponding u_1–u_2 state space organisation. Left: stable *mlp* HSS (u_1=u_2) for α_u=2.3. Right: stable IHSS (u_1>u_2 and u_2>u_1) for α_u=2.52. (B) Bifurcation-like diagram depicting the emergence of IHSS distributions with increasing number of cells N. Green boxes indicate *mlp* HSS. Red and blue stack bar markers represent distinct *u*+/*v*+ IHSS proportions. Lines connect distributions with the same proportions. (C) The symmetry-breaking population size threshold (N_{SB}) at which the HSS becomes unstable in relation to α_u. For probabilistic distance-based coupling, the median (n=200) is shown. Green-to-red/blue arrow denotes the symmetry-breaking mlp-to-*u*+/*v*+ transition at N=8 cells (orange star) for α_u=2.3. In all panels, remaining parameters are the same as used in Fig. 1D.

In principle, all cells within a population could acquire *u*+ cell type, without the *v* + cell type ever occurring.

We next investigated which type of network topology could give rise to stable heterogeneous population states. We found that the IHSS emerges for a number of different network topologies that are characterised by inhibitory coupling, i.e. topologies with an effective negative feedback on *u* via the signalling molecule *s* (Fig. S3A to C; Eqn 2). Moreover, IHSS could be also obtained for oscillatory gene expression dynamics in isolated cells (Fig. S3D, Eqn 3). The bifurcation analysis additionally implies that heterogeneous cell types will be reached even when starting from identical initial conditions, representing a true symmetry breaking event.

Interestingly, the value for α_u=2.3 used in Fig. 1D lies before the PB, what we will term herein as a subcritical organisation of the system. The bifurcation diagram for N=2 cells (Fig. 2A) can therefore explain why in the lineage tree in Fig. 1D the cells maintained the *mlp* state and did not switch to the *u*+/*v*+ cell type, but it does not explain how the transition can occur for increasing population size N. We therefore generated a bifurcation-like diagram by varying N as in the lineage tree, while keeping all parameters fixed (with α_u=2.3) and using short-range communication (Fig. 2B). We identified the distinct collective states for each N via their *u*+/*v*+ cell-type proportions. The existence of steady states was estimated with an exhaustive stochastic search, with different initial conditions and noise intensities (Materials and Methods). The identified IHSSs with equivalent proportions were grouped, and the average *u*-values were depicted separately for the *u*+ and *v* + cell types within each distribution group. This yields paired upper and lower branches, analogously to the bifurcation diagram in Fig. 2A. Whereas for N=2 coupled cells only the *mlp* HSS was detected (Fig. 2B green; corresponding to the green circle in Fig. 2A), for N=4 coupled cells stable inhomogeneous solutions with a distinct proportion could be additionally identified (red/blue *u*+/*v*+ horizontal stack bar markers). This resembled the subcritical PB observed in Fig. 2A. The identified inhomogeneous solution corresponds to one cell having high- (*u*+) and three cells having low-expressing *u* state (*v*+), or 1*u*+/3*v* + distribution. However, for larger population sizes, the homogeneous *mlp* state lost its stability and only IHSSs reflecting the two cell types with specific proportioning were identified. In other words, the growth of the population to N=8 triggered a transition from the precursor to the differentiated cell state. This demonstrates that when α_u assumes a sufficiently low value to set the system before the bifurcation point, the growth of the population can trigger a dynamical transition, resembling the one that occurs when α_u is increased (Fig. 2A).

To explore how the population size N_{SB} at which there is an occurrence of symmetry breaking depends on α_u, we performed an equivalent of a two-parameter bifurcation analysis. The diagram shows that the symmetry-breaking transition could be triggered over a distinct α_u parameter region for short-range coupling (Fig. 2C, solid line). Depending on the α_u value before the PB, the symmetry-breaking point will be realised at a distinct size of the population (N_{SB}). Thus, for subcritical organisation, differentiation timings can emerge in a self-organised manner. Similar results were also obtained for local coupling and the probabilistic distance-based coupling

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(Fig. 2C). On the other hand, for global all-to-all coupling, the symmetry-breaking transition could only be triggered stochastically with an increase in N. Therefore, these results suggest that under local and short-range coupling, as the population grows in size, the PB shifts its position towards lower α_u values. This is likely caused by the relative change in the effective communication range of the cells from global to a more local one with the size increase. The PB shift thereby enables transition of the system state from an HSS to an IHSS. Altogether, the analysis renders the number of cells as an effective bifurcation parameter that in conjunction with subcritical organisation drives the timing of cellular differentiation.

Reliable proportioning of differentiated cell types is a dynamical consequence of the sequential ordering of IHSS solutions

To investigate how the u+/v+ cell-type proportions emerge and are stabilised as the size of the population increases, we analysed the IHSS manifestation for N>2 cells in terms of bifurcation structure. For N=4 cells, the short-range and global coupling are equivalent, due to the small system size. The bifurcation analysis showed that at α_u=2.3, although for N=2 only the *mlp* HSS was stable (Fig. 2A), for N=4 coupled cells there was co-existence of the HSS and IHSS (Fig. 3A, equivalent to the result in Fig. 2B). The observed IHSS distribution was 1u+/3v+, with one cell having high- (u+) and three cells having low-expressing u state (v+), which for increasing α_u values was followed by 2u+/2v+, with two cells in each state, and 3u+/1v+, with three cells with high- and one with low-expressing u state (blue, purple and red branches in Fig. 3A, respectively). All of these distributions are associated with stable attractors that emerge from the same PB. In general, for N globally coupled cells, N−1 different distributions of cells between the u+ and v+ cell types are stable ([k]u+/[N−k]v+, for $k = \overline{1, N-1}$) (Koseska et al., 2010). These distributions are always sequentially ordered towards an increasing proportion of u+ cells for increasing α_u values. IHSS branches with adjacent distributions ([k]u+/[N−k]v+ and [k+1]u+/[N−k−1]v+) overlap, whereas the more dissimilar u+/v+ distributions are separated along the bifurcation parameter domain (Fig. 3A). Thus, for a given α_u, either a single IHSS distribution with

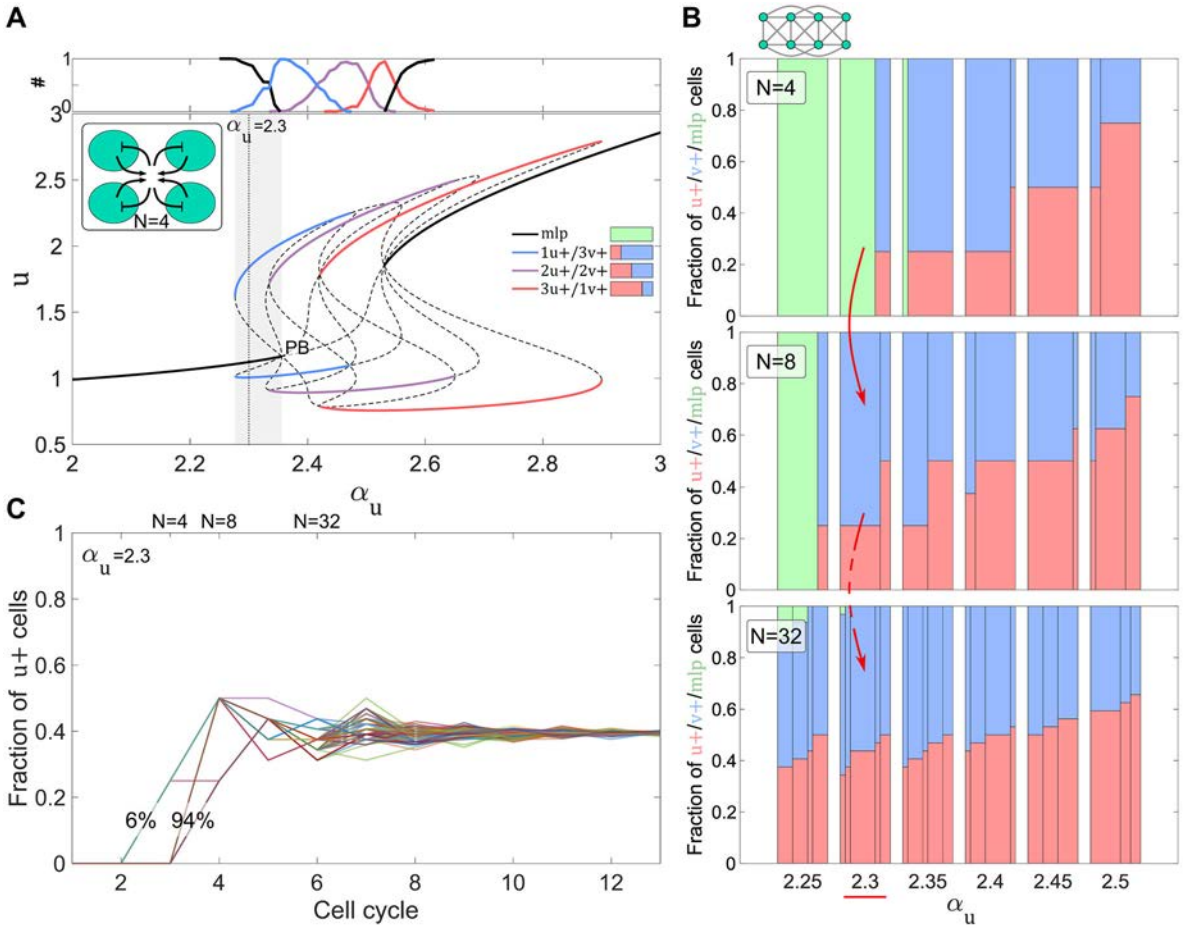

Fig. 3. Reliable cell-type proportions are established through stable IHSS distributions. (A) Bifurcation analysis for N=4 globally/short-range-coupled cells (inset). Solid lines indicate stable HSS (black) and IHSS (blue, purple and red) branches. Three stable IHSS distributions with increasing u+/v + cell-type ratios appear sequentially (key). Dashed lines indicate unstable steady states. Dotted lines indicate organisations in parameter space. The grey shaded area indicates the parameter range of HSS/IHSS co-existence for subcritical organisation. Top: probabilities for visiting IHSS distributions (y-axis) at the respective α_u values, estimated from 200 independent realisations. The initial conditions were randomly drawn from a normal distribution $\mathcal{N}(\mu_{ics}, \sigma^2_{ics})$ around the corresponding α_u-specific *mlp* state (μ_{ics}, σ_{ics}=0.2μ_{ics}). (B) u+/v+/*mlp* cell-type proportions for increasing α_u values, when a short-range coupled population of N=4 (top), N=8 (middle) and N=32 cells (bottom) on a 2×2, 2×4 and 4×8 grid is considered, respectively. The width of each sub-bar within a bar reflects the fraction of occurrence of the respective u+/v+/*mlp* proportion in ten independent realisations. Initial conditions were the same as in A (top). Red arrows indicate the progression of the distribution of stable cell-type proportions with increase of system size (N=4,8,32 cells) for α_u=2.3. (C) Temporal evolution of the fraction of u+ cells at each step of a lineage tree under short-range coupling and α_u=2.3. Results from 100 independent numerical simulations are shown. Other parameters are the same as in Fig. 1D.

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distinct cell-type proportions, or adjacent branches with similar ratios, will be predominantly visited (Fig. 3A, top).

Intrinsic cell-to-cell variability in terms of circuit parameters does not affect the ordering of IHSS distributions and thereby cell-type proportioning. This was demonstrated by a bifurcation analysis on a coupled system of four cells with non-identical α_v values (Fig. S4A). Although in this scenario there are already slightly different *mlp* values in each cell, the parameter range over which the IHSS branches are stable is expanded (Koseska et al., 2009), and the overlapping intervals between adjacent distribution branches are reduced (compare Fig. S4A with Fig. 3A). Thus, the role of cell-to-cell variability is fundamentally different in coupled multicellular systems compared with multistable single-cell systems: it does not cause the symmetry-breaking event, but rather enhances its manifestation. Overall, these results indicate that the reliable cell-type proportions that emerge as the system transits to the differentiated state at a critical population size, are an inherent property of the distribution of IHSS solutions.

To investigate whether for larger population sizes the $u+/v+$ cell type proportions are indeed related to the sequential ordering of IHSS distributions, we compared the proportions for increasing α_u values at N=4, 8 and 32 short-range coupled cells. Multiple realisations of the numerical simulations were performed when starting from initial conditions randomly drawn from a normal distribution $\mathcal{N}(\mu_{ics}, \sigma^2_{ics})$ with a mean equal to the α_u-specific *mlp* state and s.d. $\sigma_{ics}=0.2\mu_{ics}$ (Fig. 3B). For N=4, the results were identical as those obtained from the bifurcation analysis: at α_u=2.3, $1u+/3v+$ proportion was detected, transiting to $2u+/2v+$ and $3u+/1v+$ as α_u was increased (Fig. 3B, top), corresponding to the sequential ordering of the branches and the probabilities for visiting them (Fig. 3A).

For N=8 short-range coupled cells, only the IHSS solutions were stable at α_u=2.3 (Fig. 3B, middle), showing again that the differentiation occurs at the critical transition from N=4 to N=8 cells (red arrow in Fig. 3B; as in Fig. 2B). The PB was shifted to a lower α_u value (α_u=2.281), thus enabling the differentiation timing to be realised in a self-organised manner. Furthermore, the $u+/v+$ cell type proportions were stabilised as the population increased (Fig. 3B, bottom, for N=32 cells). This shows that for a given parameter organisation, defined proportions can be reliably established and reproduced through multiple simulation realisations. We also corroborated the reliability of the timing mechanism by estimating the temporal evolution of the fraction of $u+$ cells across the different stages of the lineage tree (Fig. 3C). This showed that differentiation timing at N=8 cells, following the third cell cycle, was achieved in 94% of the cases, but also, the $u+/v+$ cell type proportions were reliably and stably maintained thereafter. The reliable cell-type proportioning was also manifested for the three additional coupling scenarios (Fig. 1C). In these cases, the increase in the proportion of $u+$ cells with an increase in α_u for N=32 cells is analogous to the progression of branches in the generic bifurcation analysis (N=4, Fig. 3A), although the HSS was destabilised at different α_u values for each of them (Fig. S4B-D). The variability between the cell-type proportions for a fixed α_u value is nevertheless with a $\lesssim$5% s.d. For local coupling, specifically, a 50%−50% ratio was maintained in a large α_u interval, indicating that the probability of visiting a different IHSS manifestation increases only for higher α_u values (Fig. S4C).

Therefore, this analysis showed that although different initial conditions can lead to different IHSS distributions, in most cases these are distributions with similar cell-type proportions. Thus, (1) reliable cell-type proportioning is a result of the sequential ordering of IHSS solutions in parameter space and (2) cell-cell variability enhances the manifestation of the identified symmetry breaking solution.

The IHSS distributions confer robust cell-type proportioning and mediate its recovery from perturbations

Our demonstration that the proposed symmetry-breaking mechanism is population-based suggests that robust cell-type proportions would be generated despite differences in initial conditions, and that they can be dynamically recovered upon perturbation. To probe the robustness property, we investigated the influence of different initial conditions distributions (changing the variance or shifting the mean value) that determine the initial gene expression states in single cells, as well as the effect of gene expression noise intensity. The results were obtained for a population of fixed size, N=32 cells, under the four distinct coupling types (Fig. 1C), and a fixed α_u value before the PB as before (α_u=2.3). Sampling the single-cell initial conditions from a normal distribution with increasing s.d. around the *mlp* value (Fig. 4A, top) produced distributions with reliably conserved $u+/v+$ cell-type proportions under short-range coupling (Fig. 4A, ratios with $\lesssim$8% s.d.). This demonstrates that variance in initial gene expression at the single-cell level does not majorly affect the differentiation outcome. Rather, cell types are established in characteristic proportions within a coupled system, even when starting from broad distributions of initial conditions. However, between the different coupling types, different stable $u+/v+/mlp$ proportions were generated for this fixed α_u, in agreement with previously estimated values (Fig. 3B; Fig. S4B-D): 0.45 for short-range (Fig. 4A), 0.5 for local (Fig. S5A) and 0.4 for probabilistic distance-based coupling (Fig. S5G), whereas the HSS remained stable against moderate perturbations for global coupling (Fig. S5D). Furthermore, stochastic realisations with a stepwise shift in the initial mean value from high v-expression to high u-expression state (Fig. 4B, top) also resulted in reliable cell-type proportions (Fig. 4B; Fig. S5B,E,H). The proportions were also reliable for simulations when multiplicative white noise intensity was increased (Fig. 4C; Fig. S5C,F,I, Materials and Methods). We also observed a manifestation in which, besides populating $u+/v+$ states within the IHSS solution, few cells also populated the *mlp* state, resembling a chimera-like state (Kuramoto and Battogtokh, 2002; Abrams and Strogatz, 2004). This was observed mainly for the probabilistic distance-based coupling (Fig. S5G-I), and for the short-range coupling in rare instances (Fig. 4A). As chimera states have been predominantly characterised for systems of coupled oscillators, an additional study would be required to dynamically classify these solutions.

We next explored whether this population-based symmetry-breaking mechanism could also underlie the ability of the early embryo to re-establish exact cell-type proportions following perturbations (Martinez Arias et al., 2013). To investigate this, we performed a numerical experiment in which cells were separated according to their type after the fourth cycle of the lineage tree (N=8 cells, Fig. 1D), forming two single-type subpopulations of different sizes that could further continue to grow and divide (Fig. 4D, left and right). The initial conditions of the two new lineage trees were therefore not positioned in the vicinity of the stable steady states. The subpopulation of two coupled cells with high u-expression reverted to the only stable attractor for this system size: the *mlp* HSS. However, after two cell cycles (reaching N=8 cells), both differentiated cell types re-emerged (Fig. 4D, left). The other subpopulation of N=6 cells with low u-expression initially transiently revisited the *mlp* state (attracted and then repelled by

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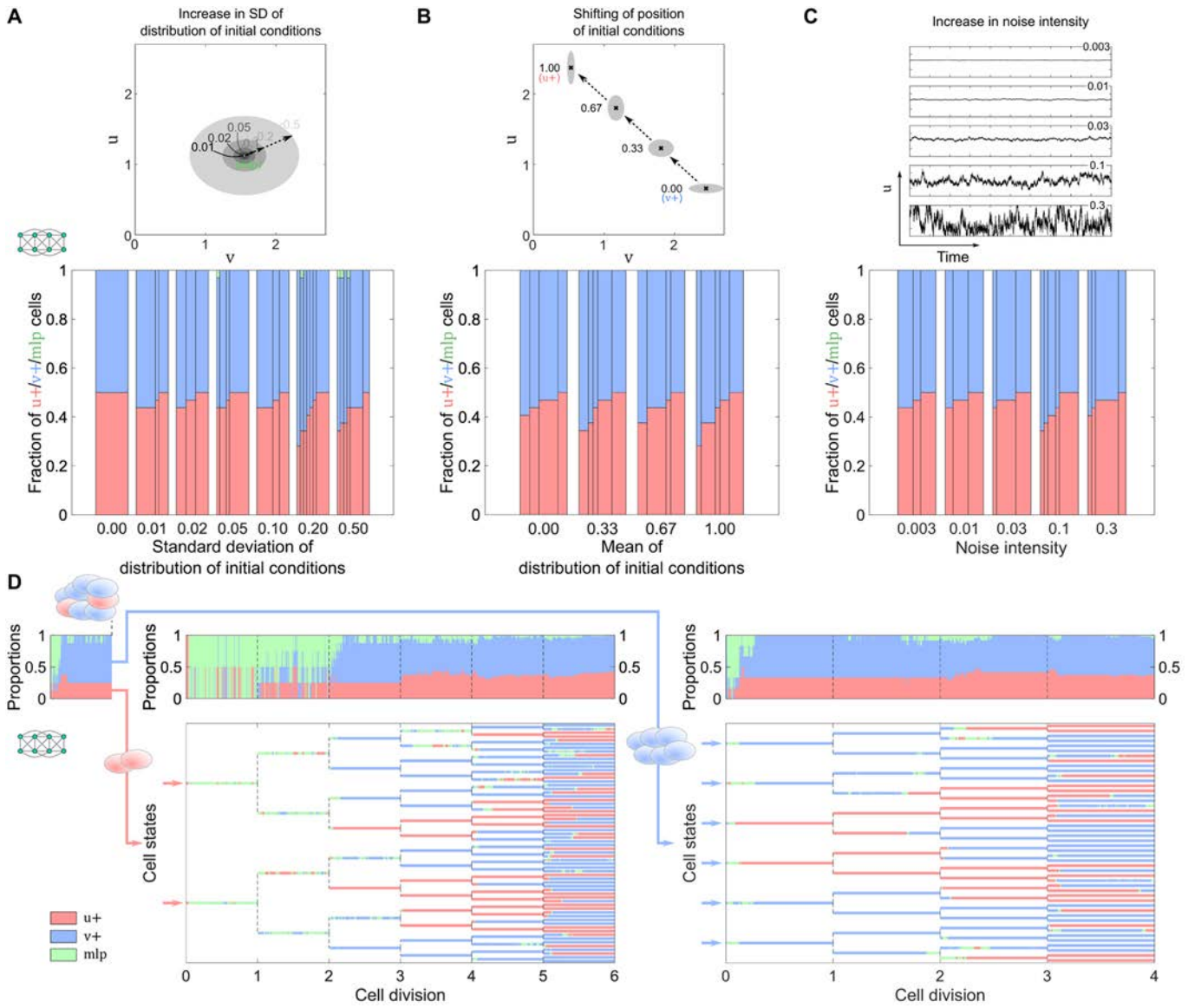

Fig. 4. Robustness in cell-type proportioning and plasticity in its re-establishment upon perturbations. (A-C) Cell-type proportions upon increase in the s.d. around the *mlp* initial conditions (as a fraction from the mean) (A); a shift in the mean of the distribution (μ_{ics}) value from high *v*-expression (μ_{v+}) to high *u*-expression cell state (μ_{u+}), with $\mu_{ics}=k\mu_{u+}+(1-k)\mu_{v+}$ for $k \in \left\{0, \frac{1}{3}, \frac{2}{3}, 1\right\}$ and $\sigma_{ics}=0.1\mu_{ics}$ (B); and an increase in the noise intensity (Materials and Methods) (C). Top: respective perturbations; 1-sigma ellipses of the distributions are depicted. Bottom: proportions from ten independent numerical realisations per condition are shown, estimated for N=32 short-range coupled cells on a 4×8 grid and organisation before the PB, α_u=2.3. (D) Lineage trees generated from homogeneous sub-populations of differentiated cells, separated at the fourth step of the lineage tree in Fig. 1D (N=8 cells). Left: lineage tree seeded from N=2 cells that previously had adopted a high *u*-expression state (*u*+). Right: lineage tree from the N=6 cells (2×3 grid) that before separation adopted the high *v*-expression state (*v*+). Upper panels show the respective cell-type proportions. Parameters are the same as in Fig. 1D.

the unstable saddle-type HSS) before both cell types stably re-emerged and the population settled in an IHSS during the first cell cycle (Fig. 4D, right).

The difference in timing between the two cases again points to a cell-number dependence in the triggering of the symmetry breaking (Fig. 2B). The cell-type ratios for both subpopulations were stabilised to a steady value similar to that of the full system before separation, and differed among the two subpopulations by ∼6%. This autonomous scaling and regenerating capability of the coupled system is a direct consequence of the properties of the IHSS solution: dynamically, it is not possible to stably populate the $u+$ without populating the $v+$ cell type. Thus, even when cells are separated such that only the cells of one type remain, the cell division and the cell-cell communication through which IHSS is established in the first place, will enable the system to recover both cell types with reliable ratios.

To confirm that both cell types and their proportions are indeed generated in a communication-dependent manner, we next investigated how inhibiting the cell-cell communication would affect the proportioning. We considered two different simulation scenarios, by implementing an increasing: (1) inhibition of α_s strength to mimic decreased production of the signalling molecules, and (2) inhibition of $\alpha_{u,s}$ strength, which effectively uncouples the dynamics of the intracellular circuit from the extracellular signalling. For this, α_s or $\alpha_{u,s}$ were effectively decreased by given multiplicative factors $(1-s_{inh,out})$ and $(1-s_{inh,in})$, respectively.

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The simulations showed that in the first scenario, decreasing the production of the signalling molecule results in an increase of the *u*+ cells proportions, abruptly transiting to a homogeneous population of high *u*-expressing cells at 25%–30% of $s_{inh,out}$ (Fig. S6A). Decreasing $\alpha_{u,s}$ on the other hand, which decreases the overall transcription rate of *u*, reduces *u*+ cells proportions to abruptly transit to a homogeneous population of low *u*-expressing cells at $\sim 9\%$ of $s_{inh,in}$ (Fig. S6B). The single cells are now weakly coupled and, for the given parameters, the system is organised in the monostable low *u*-expressing state. The lack of robustness in cell-type proportioning observed under these conditions thus underlines the importance of population-level coordination in the system.

In summary, the presented results demonstrate that a subcritical organisation in conjunction with cell division within a communicating population ensures not only the robustness of the proportions of differentiated cell types with respect to initial conditions and noise, but can also enable re-establishment of this distribution upon perturbation.

IHSS leads to reproducible spatial patterns in growing cell populations

As the differentiation mechanism described here relies on cell-to-cell communication, we investigated whether the differentiated cells were randomly distributed or organised into spatial patterns. We performed stochastic lineage-tree simulations, with 13 cell cycles as in Fig. 3C, reaching a grid size of 64×64 cells. The *u*+/*v*+/*mlp* proportions were estimated from the stable steady states at the end of each cell cycle. To characterise the spatial distribution of cells, we quantified the extent of spatial clustering as the cluster radius of the *u*+ cells. Thus, for all *u*+ cells, the fraction of *u*+ cells in their surroundings with increasing distance was estimated (Fig. S7). The cluster radius was thereby the distance at which the fraction of *u*+ cells dropped to halfway between the fraction at zero distance (equal to 1), and the global fraction of *u*+ cells (dashed line in Fig. S7).

To systematically assess how the coupling range, i.e. the extent of signalling communication, contributes to the formation of patterns with distinct spatial frequencies, we used deterministic and probabilistic coupling with different ranges (1-, 2-, 3-, 5-, and 10-range, Materials and Methods). For the deterministic coupling schemes, distinct regular spatial patterns were formed, the features of which were strongly linked with the respective coupling range: local coupling generated checkerboard-like patterns, short-range coupling generated regular patterns of small *u*+ cell clusters (see also Fig. S8A, Movie 1), whereas stripe-like patterns were observed for increasing coupling (10-) range (see also Fig. S8B, Movie 2). Example patterns from the last stage of the lineage tree are shown in Fig. 5A. The clustering radius in these cases increased with the increase of the coupling range (Fig. 5B, left). In all the deterministic coupling scenarios, the patterns and their proportions were reliably reproduced for independent realisations of the lineage-tree simulations (Fig. 5C, left).

Interestingly, the spatial frequency of the formed stable patterns was preserved as the size of the population grew. This can be particularly exemplified for the case with 10-range coupling, in which doubling in the number of stripes followed the horizontal cell division events (Movie 2). This effectively rendered the width of the stripes, i.e. the *u*+ cluster radius and the distance between them, stable across the cycles (Fig. S8B). However, initially, at around the third cycle, a lower stable fraction of *u*+ cells was established and maintained by simple state propagation through cell division, which resulted in growth of the *u*+ cluster radius, until the critical system size was reached (eighth cycle) and a stable stripe-like pattern was formed (Fig. S8B). The pattern-directed *u*+ cluster size and cell-type proportions were further stably maintained. The simulations also showed that the cell population size at which the transition to the differentiated state was triggered was also preserved (Fig. S8A-D, lower left). Even more, the formed patterns and their characteristics were also preserved for a fixed population size as in the final grid, in which cells were randomly initialised (Fig. S9A-C).

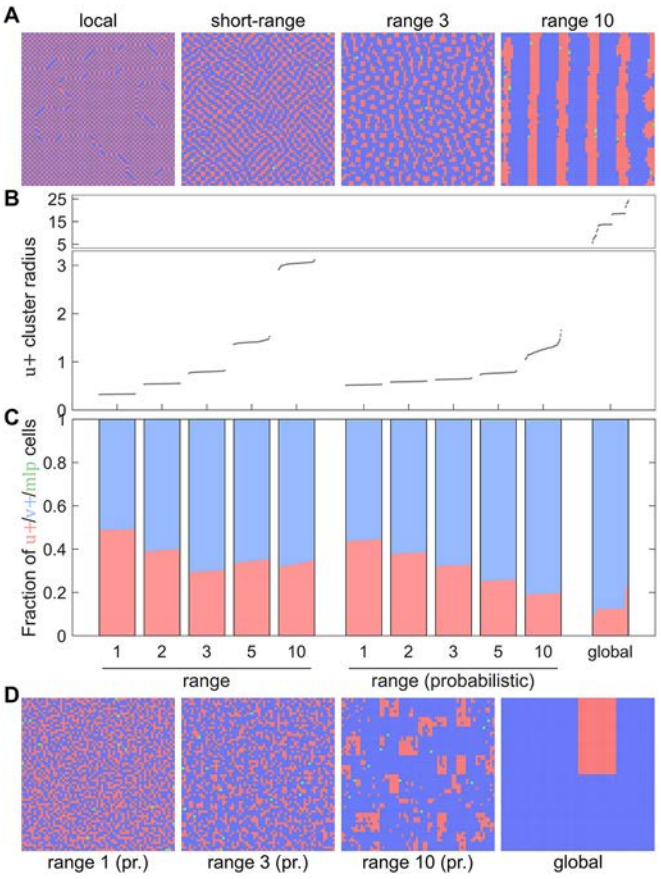

Fig. 5. Robust cell-type proportions are correlated with reproducible spatial patterns. (A) Exemplary spatial patterns for different coupling ranges: local, short-range, 3-range and 10-range coupling. (B) *u*+ cluster radius estimated at the final stable state of the lineage tree (64×64 size) for deterministic (left), probabilistic (middle) and global all-to-all coupling (right). Results from 100 independent stochastic realisations per coupling type are plotted in ascending order. (C) Corresponding *u*+/*v*+/*mlp* cell-type proportions. Bars are analogous to those in Fig. 3B. (D) Exemplary spatial patterns for range 1, 3 and 10 probabilistic coupling and global all-to-all coupling. Parameters are the same as in Fig. 1D.

On the other hand, when probabilistic distance-based coupling of different ranges was used, the lineage-tree simulations showed arrangement formation with less regular patterns (Movie 3 for 10-range coupling). Nevertheless, larger cluster size was again characteristic for larger communication ranges (Fig. 5B, middle; Fig. 5D). The proportioning was also reliably achieved over the different realisations (Fig. 5C, middle), in which the *u*+ fraction was maintained mainly by propagating the cell type from mother to daughter cells during division. Therefore, the *u*+ cluster radius is directed by the population growth, but is ultimately constrained by the communication range (Fig. S8C). That population growth highly regulated the formed patterns is also reflected through the formation of random spatial arrangements when populations of fixed size were randomly initialised (Fig. S9B-D).

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The limiting case of these observations is the global all-to-all coupling scenario, which in most of the cases resulted in the formation of a single *u*+ cell-type cluster when population growth was considered (Fig. 5D, right; Fig. S8D, Movie 4). Such spatial arrangement is a direct consequence of the daughter cells inheriting their cell type from the mother cell along the lineage tree. In this case, the cell-type proportions were maintained globally, and the states of adjacent cells did not need to readjust to maintain the respective proportions locally. The relative size of the *u*+ cluster with respect to the population size was thereby only constrained by the cell type proportions. In contrast, for a fixed population size and starting from random initial conditions, a random arrangement of cell types across the grid was observed (Fig. S9D). Thus, in systems with global all-to-all or probabilistic coupling, the growing of the population is crucial for the observed spatial organisation.

Therefore, these results suggest that the IHSS not only represents a dynamical mechanism for generating stable proportions of differentiated cell types, but also enables their reproducible arrangement in regular patterns, the frequency of which is in turn constrained by the communication range.

DISCUSSION

We have argued here that intercellular communication, an integral process in developing mammalian embryos (Saiz et al., 2020; Lorthongpanich et al., 2012), gives rise to mutually exclusive differentiated cell types (Koseska and Bastiaens, 2017) as the population grows in size. We demonstrated that both the homogeneous undifferentiated and heterogeneous differentiated cell types, as well as the transition between them, can be described without changing the model parameters. This is valid when isolated cells are characterised with monostable steady state or oscillatory gene expression dynamics. The proposed simple but scalable mechanism enables robust cell-type proportions to emerge autonomously, but also describes their reliable recovery upon perturbation. This population-based heterogeneous solution is thereby distinct from the concept that single-cell multistability together with cell-to-cell variability are necessary to describe how differentiated cell types emerge. Such a single-cell scenario does not provide a mechanism for robust proportioning between differentiated cell types, but rather relies on tight regulation of initial states and signalling.

These two conceptual views have been recently subjected to an experimental test (Raina et al., 2020 preprint) using an *in vitro* model for robust proportioning of epiblast and primitive endoderm-like cell types in mouse embryonic stem cells. Starting from a broad range of initial gene expression profiles, the wild-type populations achieved robust epiblast and primitive endoderm cell-type proportions, in contrast to a communication-deficient mutant. The experiments also showed that the proportions could be reliably re-established in the wild type upon disproportionate removal of one cell type, in line with our predictions. Therefore, these observations corroborate the proposed hypothesis that balancing between robustness of differentiated cell-type proportions, while maintaining the plasticity of the system, such that it can recover to the exact proportioning upon perturbation, requires a population-based symmetry-breaking mechanism as realised by the IHSS.

Important insights regarding symmetry-breaking mechanisms unquestionably came from Turing's seminal work (Turing, 1952), and have been widely explored to describe the emergence of spatial organisation during development (Raspopovic et al., 2014; Economou et al., 2012). The IHSS similarly provides a dynamical transition from homogeneous *mlp* to a heterogeneous state of differentiated cell types within a population. Even more, the IHSS enables a reproducible spatial arrangement of the two differentiated cell types for a broad range of coupling scenarios, irrespective of the initial conditions. We have demonstrated that the formed pattern type is tightly related to the coupling range and the specified stable IHSS distribution. The spatial patterns identified in our simulations are broadly consistent with experimentally observed patterns in cell differentiation paradigms that could potentially be governed by an IHSS. Cell differentiation in the inner cell mass (ICM), for example, is triggered by a short-range communication signal (Raina et al., 2020 preprint). In mouse embryos and ICM organoids, the two cell types differentiating from the ICM form small clusters (Mathew et al., 2019; Fischer et al., 2020), similar to what we obtain in simulations with short-range coupling.

What is unique about the bifurcation transition presented here is not only the reliability of the differentiated cell type proportions and spatial organisation, but also the timing of the differentiation event that emerges as a result. The mechanism of differentiation timing is a unique property for organisation of the parameters of the system before the subcritical PB. A similar mechanism of population-based symmetry breaking, but via supercritical PB, has been previously suggested for the Delta-Notch lateral inhibition model, when the strength of the local interaction between the two cells is varied (Ferrell, 2012). However, in this case, the differentiation timing cannot be realised and the manifestation of only a specific cell-type proportioning with likely a spatial checkerboard-like pattern can be explained. A conceptually equivalent model to Delta-Notch has been recently described for cell differentiation in the mouse blastocyst, by relying on non-autonomous switching of gene expression circuits at a specific size of the population to recapitulate the emergence of differentiated cell types (Saiz et al., 2020). Thereby, the issue of self-organised differentiation timing characteristic for early embryo development has not been addressed.

The IHSS mechanism proposed here can be also taken one step further. An extension of the proposed mechanism can be envisioned that describes pluripotency and multipotency of stem cells. Conceptually, this would correspond to a finite cascade of subsequent PBs occurring simultaneously on both branches of the existing IHSS solutions (Zakharova et al., 2013; van Kekem and Sterk, 2019). IHSS therefore represents a cooperative dynamical mechanism through which a growing homogeneous cell population can break the symmetry, a prerequisite for novel information regarding different cellular types to emerge. Organisation in the vicinity of this dynamical transition allows the comprehensive capture of not only the differentiation timing, but also how robustness and accuracy during development are generated.

MATERIALS AND METHODS

Modelling a generic cell-cell communication system

To model the coupled system (Eqn 1), single cells were distributed spatially on a regular two-dimensional lattice, the dimensions of which are specified throughout the figures. The cells were coupled through paracrine signalling communication, by secreting and sensing the signalling molecule *s* within a certain distance. Four different communication ranges, *R*, were mainly considered, forming distinct network couplings (Fig. 1C): globally connected network (all-to-all communication, $R=\infty$); locally connected network (cells communicate only with adjacent cells on the lattice, $R=1$, i.e. within a unit lattice distance); short-range connected network (cells communicate with cells within distance $R=2$, i.e. with adjacent cells and second-adjacent cells on the lattice); and probabilistic distance-based coupling [cells establish communication with other cells with probability $e^{-(d^2/2R^2)}$, where *d* is the Euclidean cell-cell distance and $R=1$ in the default case]. No-flux or insulation boundary conditions on the lattices were used,

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hence cells near the boundaries had fewer communicating neighbours, as exemplified by the schematic for short-range coupling on a 2×4 grid in Fig. 1C. In all cases, $s_{i,ext} = (1/(|N(i)|+1)) \sum_{j\in(N(i)\cup i)} s_j$ is the external amount of signal perceived by cell i, depicted as the averaged secreted signal from its communicating neighbourhood $N(i)$ (including itself) at every time instance, thus assuming an immediate mixing of s.

Each gene regulation term takes the renormalised Hill-type function form, $x^n/(1+x^n)$ for activation or $1/(1+x^n)$ for repression, and is therefore sensitive to values of the order of 1 of the transcription factor input x. The corresponding maximal transcription rates are α_u, α_v, α_s and $\alpha_{u,s}$, whereas β, γ, δ and η are the Hill coefficients. The reaction rates are globally scaled by λ. Values of α_u=2.3, α_v=3.5, α_s=2, $\alpha_{u,s}$=1, $\beta=\gamma=\delta=\eta$=2 and λ=50 were used throughout the study, unless noted otherwise. For the case of non-identical cells (Fig. S4A), the α_v parameter was uniformly varied between the cells in the range from −1% to 1% of its default value.

For the stochastic simulations (Fig. 1D, Fig. 2B, Fig. 3C, Fig. 4B-D, Fig. 5; Fig. S5B,C,E,F,H,I, Figs S8, S9, Movies 1-4), a stochastic differential equation model using Eqn 1 was constructed by adding a multiplicative noise $\sigma X \Delta W_t$, where ΔW_t is the Wiener process term, i.e. a normally distributed random variable with zero mean and variance Δt, whereas X is a state variable ($X\in\{u_1, v_1, s_1, \ldots, u_N, v_N, s_N\}$). The model was solved with Δt=0.01 using the Milstein method (Mil'shtein, 1974), by adding a second-order approximation term $0.5\sigma^2 X(\Delta W_t^2 - \Delta t)$. In the cases when the noise intensity σ was not varied, it was set to 0.1.

To discriminate between the multilineage-primed- (*mlp*), *u*-positive (*u*+) or *v*-positive (*v*+) cell types for a given realisation, each marginal cell state vector (u_i, v_i, s_i) within the converged state of the system (IHSS or HSS) was individually categorised as one of three cell types and the three-term *u*+/*v*+/*mlp* ratio (proportions) in the population was subsequently calculated. The reference *mlp* state vector (u_{mlp}, v_{mlp}, s_{mlp}) was predetermined for a given parameter set, i.e. for a specific value of α_u, from the respective steady-state value of the 1-cell monostable system realisation (as in Fig. S2A), as the bifurcation analysis demonstrated that the *mlp* HSS for single-cell and cell-to-cell coupled systems is equivalent. Every marginal cell state (u_i, v_i, s_i) for $i = \overline{1,N}$ of a deterministic realisation was categorised as *mlp* cell type when its value fell within 1% around the predetermined *mlp* state vector, whereas cell states whose u_i/v_i ratio was larger than the u_{mlp}/v_{mlp} ratio of the *mlp* state were assigned *u*+, and otherwise *v*+ cell types. Transient states during the stochastic realisations in Fig. 1D, Fig. 4D and Movies 1-4 were categorised as *mlp* type if they fell within 5% around the deterministic *mlp* state. End states of all stochastic realisations were allowed to converge to their deterministic attractor state in noise-free fashion before categorising (with 1% s.d. around the *mlp* state), as in Fig. 3C, Fig. 4B,C, Fig. 5; Figs S5B,C,E, F,H,I and Figs S8, S9.

Initial conditions for all cells and variables were independently randomly sampled from a normal distribution $\mathcal{N}(\mu_{ics}, \sigma_{ics}^2)$, typically around the corresponding α_u-specific *mlp* state vector (u_{mlp}, v_{mlp}, s_{mlp}) as the mean (μ_{ics}), and with $\sigma_{ics}=0.1\mu_{ics}$ or $\sigma_{ics}=0.2\mu_{ics}$, as denoted in the respective figures. α_u-specific *mlp* states correspond to the steady-state values in the single-cell system (Fig. S2A). For Fig. 4A and Fig. S5A,D,G, σ_{ics} was increasing from 0 to 50% of the respective *mlp* value (μ_{mlp}). For Fig. 4B and Fig. S5B,E,H, μ_{ics} values were shifted stepwise along the line segment from a typical *v*+ cell state (μ_{v+}) towards a typical *u*+ cell state (μ_{u+}), using $\mu_{ics}=k\mu_{u+}+(1-k)\mu_{v+}$ for $k \in \left\{0, \frac{1}{3}, \frac{2}{3}, 1\right\}$, and with $\sigma_{ics}=0.1\mu_{ics}$.

Finally, for the results from ten repetitions, in which the identified IHSSs with equivalent proportions were grouped, each proportion was plotted as a stacked sub-bar within a bar plot, the width of which corresponded to the fraction of occurrence of that proportion in the simulations. Proportions were plotted in ascending order of their *u*+ cell-type fractions. The results from 100 repetitions (Fig. 5; Fig. S9) were plotted equivalently, without vertical lines separating the sub-bars of the proportions.

Estimating IHSS distributions as a function of the number of cells

In Fig. 2B, the different branches of the IHSS (and the proportions of cells in them) were estimated by analogy to Fig. 2A, but here using the number of cells as a bifurcation parameter. For this, exhaustive scanning was performed to locate the different fixed point attractors in the state space for each N. The scanning process involved 20 repetitive executions with different noise intensities (varying from 0 to 0.3). Each repetition consisted of 30 alternating cycles of stochastic execution (for exploration), followed by deterministic execution (for convergence to an attractor), when the reached state was tested for stability and subsequently recorded. For every distinctly detected attractor, the *u*+/*v*+/*mlp* proportion of cells was estimated, and attractors with equivalent proportions were grouped. The average *u* values were calculated separately for both *u*+ and *v*+ cell types for each proportion, and plotted as branches (*u*+ and *v*+ cells for IHSS, or *mlp* cells for HSS; colour-coding as in Fig. 2A), in analogy with the bifurcation diagrams in Fig. 2A and Fig. 3A. Chimera-like states were omitted from the diagram for simplicity.

Lineage tree generation

The generation of lineage trees was performed using stochastic simulations in which the system doubles in size at regular time intervals, starting from a single-cell system (Fig. 1D), unless otherwise specified (Fig. 4D). At every cell division, the final state of the mother cell is passed on to the initial conditions of the daughter cells. Cell divisions occur along the horizontal and vertical axes on the grid alternately, sequentially yielding lattices of 1×1, 1×2, 2×2, 2×4, 4×4, 4×8, 8×8, etc., as demonstrated in Fig. S1. Cellular states were categorised in every time instance to plot the single-cell temporal evolutions in the lineage trees (Fig. 1D, Fig. 4D). Furthermore, cellular proportions in the system were estimated from those values, and their temporal evolution was shown in the panels above the lineage trees. The fraction of *u*+ cells was plotted to yield Fig. 3C, Fig. 5C, Fig. S8 (lower left plots) and Fig. S9C.

In the cell-type separation case (Fig. 4D), the states of the cells at the end of the fourth cycle (from Fig. 1D) were categorised and the differentiated cells were then separated: *u*+ cells were given as seeds to a new lineage tree (1×2 grid), whereas *v*+ cells were seeds for a separate one (2×3 grid). Following this, multiple cell divisions were again performed and the cell proportions were estimated.

Analysis of spatial patterns

To characterise the spatial organisation of the system, lineage tree simulations with an extended duration of 13 cell cycles were performed, reaching a final size of a 64×64 grid. Both for deterministic and probabilistic distance-based coupling, communication with ranges of 1, 2, 3, 5 and 10 were considered. Additionally, global coupling was also used.

Spatial organisations were analysed at the end of each cell cycle, after the collective state reaches a steady state in a noise-free fashion. Fractions of *u*+/*v*+/*mlp* cells were quantified for the final spatial configuration (64×64 grid), and the results from 100 different repetitions were grouped as stacked bars. Moreover, the fractions of *u*+ cells were quantified for the end state of each cell cycle to track the development of the lineage tree (Fig. 3C; Fig. S8). The percentage of the numerical simulation realisations that showed symmetry breaking following a certain cell division cycle are also denoted on the plots (Fig. S8, lower left plots). Histograms depicting the proportion of numerical simulation realisations upon which a specific *u*+ cell-type fraction was reached in the final state of the lineage tree are also shown (Fig. S8, lower left plots).

To characterise the spatial clustering, the average *u*+ cluster radius was estimated from the spatial configurations by calculating for all *u*+ cells the fraction of *u*+ cells in the surround within increasing distance (Fig. S7). The cluster radius is therefore the distance by which the fraction of *u*+ cells drops to halfway between the fraction at zero distance (equal to 1), and the global fraction of *u*+ cells (dashed lines in Fig. S7), which is analogous to calculating half-life from exponential decay. The results from the realisations were plotted as single points in ascending order for each coupling range type in Fig. 5B and Fig. S9B. As with the fraction of *u*+ cells, the *u*+ cluster radius was also tracked over the development of the lineage tree, with a histogram being plotted for the final state as well. Both measures were also estimated when considering a population with a fixed size (64×64 grid), and starting from random initial conditions ($\mu_{ics}=\mu_{mlp}$, $\sigma_{ics}=0.1\mu_{ics}$) (Fig. S9).

The lineage tree simulations shown in Movies 1-4 were performed with a reduced number of time points (2000) per cell cycle to yield shorter movies. Spatial configurations with stochastic categorisation of the cell types were

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saved for every tenth time point, and the saved frames were combined in a movie of 60 frames per second.

Decreasing cell-cell communication strength

For Fig. S6A, deterministic simulations were performed for a fixed population size on a 4×8 grid, short-range coupling (other parameters as in Fig. 1D) and starting from random initial conditions ($\mu_{ics}=\mu_{mlp}$, $\sigma_{ics}=0.1\mu_{ics}$). To model the decreased cell-cell communication strength, an inhibitory multiplicative term ($1-s_{inh,out}$), where $s_{inh,out}\in\{0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3\}$, was introduced to the first term in the equation for s in Eqn 1. This enabled the effective reduction of the production strength of s by a given percentage. The corresponding results from ten independent realisations for each condition are presented in Fig. S6A.

Similarly, for Fig. S6B, an inhibitory multiplicative term ($1-s_{inh,in}$), where $s_{inh,in}\in\{0, 0.0153, 0.0307, 0.046, 0.0613, 0.0767, 0.092\}$, was introduced to the second term in the equation for u in Eqn 1. Other settings were the same as for Fig. S6A.

Additional cell-cell communication systems exhibiting population-based symmetry breaking

To demonstrate the generality of the population-based symmetry-breaking mechanism via a PB, we also tested several minimal network topologies with effective negative feedback coupling on u via s (Fig. S3A-C). Their dynamics were described using the following system of equations:

$$\begin{aligned}\frac{1}{\lambda}\frac{\mathrm{d}u_i}{\mathrm{d}t}&=\alpha_u\frac{1}{1+v_i^{\beta}}+\alpha_{u,s}\frac{1}{1+s_{i,ext}^{\eta}}-u_i\\ \frac{1}{\lambda}\frac{\mathrm{d}v_i}{\mathrm{d}t}&=\alpha_v\frac{1}{1+u_i^{\gamma}}+\alpha_{v,s}\frac{s_{i,ext}^{\eta}}{1+s_{i,ext}^{\eta}}-v_i\\ \frac{1}{\lambda}\frac{\mathrm{d}s_i}{\mathrm{d}t}&=\alpha_s\frac{u_i^{\delta}}{1+u_i^{\delta}}+\alpha_{s,v}\frac{1}{1+v_i^{\delta}}-s_i.\end{aligned}\tag{2}$$

For Fig. S3A, $\alpha_{u,s}=0$, $\alpha_s=1$, $\alpha_{v,s}=1$, $\alpha_{s,v}=0$ and $\alpha_v=2.75$. For Fig. S3B, $\alpha_{u,s}=0.5$, $\alpha_s=0$, $\alpha_{v,s}=0$, $\alpha_{s,v}=3$ and $\alpha_v=3$. For Fig. S3C, $\alpha_{u,s}=0$, $\alpha_s=0$, $\alpha_{v,s}=1$, $\alpha_{s,v}=2$ and $\alpha_v=3$.

Paradigmatic model mimicking the vertebrate neurogenesis process

It has been previously demonstrated that the presence of time delays in models of lateral inhibition can result in significant oscillatory transients before patterned steady states are reached. The impact of local feedback loops in a model of lateral inhibition based on the Notch signalling pathway, elucidating the roles of intracellular and intercellular delays in controlling the overall system behaviour, has also been proposed (Momiji and Monk, 2009). Here, we aimed to understand whether population-based PB can provide the dynamical background behind the observed symmetry-breaking phenomenon. As our aim was to demonstrate the validity of this concept, we omitted the molecular details of the Notch pathway example and modelled a generic case in which the gene expression dynamics in each cell were characterised by oscillatory behaviour, whereas intercellular communication between the N cells was realised in a global manner, for simplicity (N=2, Fig. S3D). The dynamics of the system were therefore described as:

$$\begin{aligned}\frac{\mathrm{d}p_i}{\mathrm{d}t}&=\alpha_p\frac{1}{1+q_i^{\beta}}+\alpha_{p,r}\frac{r_i^{\eta}}{1+r_i^{\eta}}-p_i\\ \frac{\mathrm{d}q_i}{\mathrm{d}t}&=\alpha_q\frac{1}{1+p_i^{\gamma}}-q_i\\ \frac{\mathrm{d}r_i}{\mathrm{d}t}&=\epsilon\left(\alpha_r\frac{1}{1+p_i^{\gamma}}-r_i\right)+2d(r_{i,ext}-r_i)\\ \frac{\mathrm{d}r_{i,ext}}{\mathrm{d}t}&=\frac{de}{N}\Sigma_j(r_j-r_{i,ext}).\end{aligned}\tag{3}$$

Here, p and q are two genes that mutually inhibit the expression of each other, r controls the production of the signalling molecule, the extracellular concentration of which is denoted as r_{ext}. This system has been demonstrated to exhibit synchronised oscillations in a population of communicating cells (Kuznetsov et al., 2004; Koseska et al., 2007). The parameters are as follows: α_q=5, $\alpha_{p,r}$=1, α_r=4, β=2, γ=2, η=2, ϵ=0.01, d=0.008 and de=1.

The numerical bifurcation analysis was performed using the XPP/AUTO software (http://www.math.pitt.edu/~bard/xpp/xpp.html). All simulations were performed using custom-made code in MATLAB (MATLAB and Statistics Toolbox Release R2020b, MathWorks).

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Competing interests

The authors declare no competing or financial interests.

Author contributions

Conceptualization: A.K.; Methodology: A.S., A.K.; Software: A.S.; Validation: A.S., C.S., A.K.; Formal analysis: A.S.; Investigation: A.S., A.K.; Writing - original draft: A.K.; Writing - review & editing: A.S., C.S., A.K.; Visualization: A.S.; Supervision: A.K.

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Data availability

All data and code used in this study are available at www.github.com/astanoev/SymmetryBreaking.

Supplementary information

Supplementary information available online at https://dev.biologists.org/lookup/doi/10.1242/dev.197608.supplemental

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