and the HLA-A2 peptide binding domain. Although the conformational changes are consistent with a classical induced fit mechanism, further investigations using fluorescence anisotropy, proline mutagenesis, and molecular simulations revealed that the conformational changes were triggered instead by the presence of peptide-specific conformational dynamics in the HLA-A2 protein as well as flexibility in the TCR CDR loops. Overall, the results indicate that A6 recognition of the Tel1p peptide requires the mutual adaptation of two flexible molecules, with the degree of flexibility in the peptide/MHC complex dependent on the nature of the presented peptide. These findings have implications for the nature of TCR binding and cross-reactivity and shed new light on how structural diversity can be presented to and accommodated by receptors of the immune system.

2215-Plat

Mechanical Unbinding of Leukocyte Function-Associated Antigen-1 with ICAM-1 and ICAM-3 Complexes involves a Single Energetic Barrier

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Integrin belongs to a family of proteins that play crucial roles in both cell adhesion and signal transduction. Integrins on leukocytes (leukocyte function-associated antigen-1 or LFA-1) bind to intercellular adhesion molecules (ICAMs) to facilitate the adhesion and the migration of the cell to an inflammatory site. Recently, Moy et al. probed the unbinding of LFA-1 with ICAM-1 and ICAM-2 using AFM at the single-molecule level. They observed two separate regimes where the most probable unbinding force depended linearly on the logarithm of the loading rate and interpreted the two-regime behavior as the crossing of two free energy barriers. In the present work, we used coarse-grained Brownian Dynamics simulation to study the mechanical unbinding of LFA-1 from ICAM-1 and ICAM-3. We observed that the force-loading rate curves also displayed the fast and slow loading regimes, and the extracted kinetic parameters according to the Bell and Evans models were in quantitative agreement with those extracted from the experimental data. Moreover, employing the force-clamp mode, we found only a single energetic barrier and the two regimes resulted from an abrupt change in the transition state position. We expect similar results for the LFA-1/ICAM-2 complex, whose PDB structure is thought to be similar but not yet available.

2216-Plat

Predicting the Interactions between PDZ Adapter Domains and Disordered Peptides

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PDZ domains, one of the most ubiquitous and important scaffolding modules in human proteins, bind the disordered C-terminus of plasma membranes, mediating protein-protein interactions. Experiments have demonstrated that dissimilar C-terminal peptides bind to the same PDZ domain and different PDZs can bind the same peptides. Crystallographic studies revealed that binding to the PDZ domains requires a four residue long strand anchored by a C-terminal hydrophobic residue. Based on this information, we developed a novel semi-flexible docking method to model the peptide-PDZ complex structure and estimate its absolute affinity. The method has been tested on a set of 126 15-residue long natural peptides binding to PDZ3 of PSD95. The resulting sensitivity and specificity rates were 90.91%/79.13% by defining a kinetic and a thermodynamic threshold. Moreover, complex structures of 5 different peptides bound to PDZ domains were successfully recovered as the top ranked predicted models. This general structure-based technology is the first de novo approach to dock disordered peptides, providing a needed complementarity to proteomic assays to mine GeneBank for new targets of scaffold proteins and to predict novel protein-protein interactions. Our findings also reveal that the four-residues C-terminal recognition motif leads to only a weak non-specific binding intermediate complex, while an extended network of contacts established by the next three to five unconstrained residues determines the high specificity of the complex.

2217-Plat

Statistics and Physical Origins of pK and Ionization State Changes Upon Protein-Ligand Binding

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We investigate statistical prevalence and overall physical origins of changes in charge states of receptor proteins upon ligand binding. These changes are explored as a function of ligand type (small molecule, protein, and nucleic acid), and distance from the binding region. Standard continuum solvent methodology is used to compute pK changes upon binding for a total of 5899 ionizable residues in 20 protein-protein, 20 protein-small molecule, and 20 protein-nucleic acid high resolution complexes. The size of the dataset combined with an extensive error and sensitivity analysis allows us to make statistically justified conclusions: in 60% of all protein-small molecule, 90% of all protein-protein, and 85% of all protein-nucleic acid complexes there exists at least one ionizable residue that changes its charge state upon binding at physiological conditions (pH=6.5). Considering the most biologically relevant pH range of 4 to 8, the number of ionizable residues that experience substantial pK changes (> 1.0) due to ligand binding is appreciable: on average, 6% of all ionizable residues in protein-small molecule, 9% in protein-protein, and 12% in protein-nucleic acid complexes experience a substantial pK change upon ligand binding. Most of the change occurs in the immediate binding interface region, where about one out of five ionizable residues experiences substantial pK change regardless of the ligand type. However, the physical origins of the change differ between the types: in protein-nucleic acid complexes, the pK values of interface residues are predominantly affected by electrostatic effects, whereas in protein-protein and protein-small molecule complexes structural changes due to the induced-fit effect play an equally important role. In protein-protein and protein-nucleic acid complexes, there are a statistically significant number of substantial pK perturbations, due to the induced-fit structural changes, in regions far from the binding interface.

Platform AN: Regulatory Networks & Systems Biology

2218-Plat

Probing Multicellular Dynamics in *xenopus Laevis* Embryonic Development through Microfluidic Feedback Control

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Long-term spatiotemporal regulation of chemical environments in and around cells or tissues is critical to understand developmental signaling where dynamic responses to chemical factors control the subsequent coordinated events in development. Although progress has been made in the manipulation of single cell environments, both long-term and high-speed regulation of multicellular stimulation in developmental organisms is still challenging. We have developed a novel microfluidic feedback control system that allows long-term and high-speed manipulation of a laminar flow interface in a microfluidic channel for probing developmental systems. Our approach enabled long-term spatiotemporal manipulation of chemical environments of Animal Cap (AC) explants during the gastrulation stage in *Xenopus laevis* embryonic development. We present time and frequency responses of AC explants to periodic stimulation of steroid hormone dexamethasone (DEX) by tracking a hormone-activated nuclear-localizing green fluorescent protein tagged glucocorticoid receptor (GR) that can report the localized activity of DEX in the explants. We examine the sensitivity of GR-complex translocation to DEX concentration and frequency of stimulation. Concentration and frequency are critical factors when analyzing multicellular developmental systems such as *Xenopus*. We believe that our approach will be useful in diverse areas including biophysics, embryonic development, and engineering spatiotemporally integrated biological responses.

2219-Plat

Cells Respond Digitally to Variation in Signal Intensity via Stochastic Activation of NF-κB

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Cells detect and process spatiotemporal signals and activate gene regulatory pathways in response. Here we use high-throughput microfluidic cell culture, quantitative gene expression analysis and mathematical modeling- to investigate how mammalian cells detect external concentrations of the signaling molecule TNF-α and relay information to the gene expression programs via the transcription factor NF-κB. We measured NF-κB activity in thousands of fluorescently labeled live cells with single-cell resolution with a temporal resolution of 6 minutes and for durations up to 12 hours under TNF-α concentrations covering 4 orders of magnitude. TNF-α induced mRNA levels of 23 genes were measured and quantified at the same concentration range and duration, linking the transcription factor dynamics to the gene expression. A stochastic model was developed that reproduces the single-cell dynamics and gene expression profiles at all measured conditions, constituting a broadly applicable model for TNF-α induced NF-κB signaling. We find, in contrast to population studies, that the activation is a discrete process at the single cell level with fewer cells responding at lower doses. Nevertheless, the activated cells respond robustly

and early genes are upregulated even at the lowest TNF-α concentrations, indicating digital signaling to gene expression. Late gene expression requires persistent NF-κB activity that is induced only at highest signal levels. The measurements reveal the activation threshold, a hypersensitive dynamic range and saturation, and shows that as few as two bound receptors can activate the pathway. The cells further encode TNF-α concentration information by modulating the temporal dynamics of NF-κB, with higher concentrations resulting in faster activation and more oscillations. Our results -in addition to their biological significance- highlight the importance of high-quality, high-throughput measurements at the single-cell level in understanding how biological systems operate.

2220-Plat

Quantitative Test for Mirror Symmetry Relationship between Sister Cells

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Cell shape determination is a dynamical process modulated by input from genetic and signaling pathways. In order to understand cell morphology as a dynamical system it is critical to determine the degree of spatial inheritance, that is, the degree of influence of spatial organization within a mother cell on the organization of her daughter cells. Visual comparison of symmetry relations between daughters was used by Albrecht-Buehler to probe spatial inheritance in a series of papers published in the 1970's. His results, that sister cells are sometimes mirror images of each other, were interpreted as reflecting spatial inheritance during cell division. We have reinvestigated these claims using quantitative image analysis and several different shape-comparison algorithms to test the symmetry relations between sister cells. Applying these methods to fixed and live RPE-1 and NIH 3T3 cells, we obtained the following results: (A) sister cells are quantitatively more similar in shape than pairs of unrelated cells, (B) When sister cells show a significant degree of shape similarity, they tend to be related by mirror symmetry, (C) the shape similarity between sister cells is highest soon after division and decays on a time scale of several hours, (D) the set-theoretic union of the two sister cell shapes is related to the shape of the mother with a degree of similarity that decays as a function of time before and after division. We have also developed methodologies to compare similarity of internal actin stress fiber organization between sisters and to compare the migration trajectories of sister cells as they move away from the site of division.

2221-Plat

Tuning the Range and Stability of Multiple Phenotypic States with Coupled Positive-Negative Feedback Loops

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The ability of a cell population to maintain simultaneously multiple phenotypic states is crucial for cell fitness. It is well known that the presence of a positive feedback is sufficient to generate multistability. However, many transcription networks contain counteracting positive and negative feedbacks, which indicates that this multiloop design provides additional advantages. Through an experimental and computational study in an interlinked positive and negative feedback motif in which each feedback strength is modulate independently, we explore the dynamic properties of this interlinked network. Our results show that the transition rates between different phenotypic states are not modulated by the positive, but only by the negative feedback strength. These results indicate that the negative feedback strength determines the phenotypic behavior of the cell populations, modulating the range and stability of different multistable states. By measuring noise levels in mRNA expression we show that this differential behavior is possible because noise levels are modulated independently by each feedback motif inside this genetic network. This suggests that in this coupled design, the strength of the negative feedback loop may be tuned to allow a population to enhance its fitness by changing the rate of stochastic transitions between different states, thus ensuring that cells may be prepared to confront a given level of environmental fluctuations.

2222-Plat

The Effects of Spatial Heterogeneity and in vivo Crowding on the Lac Genetic Circuit

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Standard deterministic and stochastic models used to explore the dynamics of cellular biochemical networks typically ignore spatial degrees of freedom (by assuming the cell is well-stirred). Spatial heterogeneity has been neglected due to the lack of both data regarding cellular localization and computational methodologies to simulate such models. Advances in *in vivo* imaging techniques, including cryo-electron tomography and single-molecule fluorescence microscopy, have begun to reveal the organization and dynamics of biomolecules inside the cell. Likewise, graphics processing units (GPUs) now provide the computational power to perform three-dimensional simulations of cell-scale models. Here, the effects of incorporating spatial information and molecular crowding into a stochastic model of the lactose utilization genetic circuit are reported. We use our recently developed lattice-based Monte Carlo simulation technique [1] to sample the reaction-diffusion master equation describing the lac circuit in an *Escherichia coli* cell. Parameters are obtained from published *in vivo* single molecule studies. By comparing to the well-stirred model, it is shown that spatial degrees of freedom introduce a source of noise into the circuit. Such spatial noise is a component of the extrinsic noise of a genetic system and we put bounds on its contribution. In certain fluctuating environments, spatial noise is found to influence the switching properties of the circuit leading to population distributions that cannot be predicted using well-stirred models. Finally, the model suggests new single molecule experiments to probe the lac circuit and provides estimates of the spatial and temporal resolution required. The integration of lattice microbe models with systems biology descriptions of cellular networks is also discussed.

[1] Roberts, Stone, Sepulveda, Hwu, and Luthey-Schulten, ''Long time-scale simulations of *in vivo* diffusion using GPU hardware'', In *The Eighth IEEE International Workshop on High-Performance Computational Biology* (2009).

2223-Plat

Macroscopic Kinetic Effect of Cell-To-Cell Variation in Biochemical Reactions

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Genetically identical cells under the same environmental conditions can show strong variations in molecular content such as in protein copy numbers due to inherent stochastic events in individual cells. We here develop a theoretical framework to address how variations in enzyme abundance affect the collective kinetics of metabolic reactions observed with a population of cells. Kinetic parameters measured at the cell population level are shown to be systematically deviated from those of single cells, even within populations of homogeneous parameters. The Michaelis-Menten kinetics, besides, can be destroyed at such population level. Our findings elucidate the novel origin of discrepancy between *in vivo* and *in vitro* kinetics, and offer the potential utility of single-cell metabolomic analysis.

2224-Plat

On Population Heterogeneity and Coexistence of Bacteria and Phage

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Population dynamics experiments using bacterium Escherichia coli and phage lambda are carried out in a well-mixed environment. In all trials, the long-term behavior is the coexistence of the bacterial and the phage populations. This outcome is remarkably insensitive to various experimental conditions such as the initial bacterial population size and the initial infection ratio. Upon isolation of survival bactaria and regrown in a phage-free environment, the newly generated bacteria exhibit phage sensitivity similar to their parental cells. Thus the coexistence of bacteraium and phage is not due to genetic mutation but is intrinsic to nonlinear dynamics of the interacting species. Our measurements showed that the bacterial population is sustained by a small number of persistors that provide ''physiological refuge'' against phage infection. The measured bacterium and phage population dynamics can be reasonably account for by a simple mathematic model that takes into account stochastic switching between normal cells and persister cells.

2225-Plat

Driving DNA Tweezers with an in vitro Transcriptional Oscillator

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