transfer affected the dynamics. The result confirmed experimental observation that the T89V mutation has no effect on the capacity of the mutant to pump protons, and the calculations indicated that the OH moiety of T89 is not essential for proton transfer reaction.

The success of Fischer and coworkers extends far beyond the special problem of the initial proton transfer step of Bacteriorhodopsin. Once the methodology has passed the test and can reliably reproduce the experimental observations, it can be used as a research tool for dissecting the mechanism and predicting the sequence of events in other enzyme systems.

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Structurally Analogous Proteins Do Exist!

The structure of a random protein sequence selected in vitro for ATP binding (Lo Surdo et al., 2004) resembles the treble clef zinc binding motif. Since this artificial protein does not share a common ancestor with any natural treble clefs, it exemplifies the existence of structural analogs.

Similarity between protein shapes and folds are rationalized in terms of homology or analogy. Homologous proteins inherited their similarities from a common ancestor and structural analogs arrived at them independently. Homology provides the most parsimonious explanation of similarity, but analogy is argued for because of the simplicity and regularity of protein folding patterns. This simplicity makes it conceivable that two structures are similar not because of their evolutionary connection, but by chance, due to the limited number of ways nature can place a few secondary structural elements around each other. It is generally accepted that if two structures are rather similar and reasonably complex, then they are probably homologous. If the structures are less similar and in addition very simple, they are probably analogous. However, due to the absence of clear-cut criteria, rationalization of the structural similarity in terms of homology or analogy is not straightforward and even changes with time. In the early days of crystallography, it was more traditional to infer analogy. For instance, 8-fold pseudosymmetric β/α-barrels (TIM barrels) that are found in many groups of enzymes were regarded as classic examples of analogy: i.e., unrelated proteins adopting similar structures because of the general packing and folding rules (Lesk et al., 1989). However, with the development of more sophisticated methods of sequence and structure analysis, it became clear that most TIM barrels are likely to share a common origin and thus are homologous (Nagano et al., 2002). Nowadays, homology has become the default explanation for the majority of structural similarities. Are we pushing homology too far?

The main problem here is that evolutionary concepts are difficult if not impossible to probe experimentally. Many researchers would argue that evolution happened once and thus by definition is not subject to experiment. However, it is possible to experiment with evolutionary rules and to see what is likely and what is not. For example, it is possible to demonstrate experimentally that analogous structures exist. In fact, this has been done as an unintentional by-product of the recent study by Lo Surdo et al. (Lo Surdo et al., 2004). Lo Surdo et al. report the crystal structure of a protein domain selected from a large pool of random sequences and optimized by function-directed in vitro evolution (Keefe and Szostak, 2001). Although the artificial nucleotide binding protein (ANBP) was selected for ATP binding only, in addition to ADP, the crystal structure also revealed a zinc ion bound to four cysteine residues (Lo Surdo et al., 2004) (Figure 1A). The authors describe the structure of ANBP as belonging to a novel fold. While this is true if one considers the details of the structure, we find it most amazing that the zinc binding region of the structure displays a strong resemblance to a large and diverse group of zinc binding proteins known as treble clef fingers (Grishin, 2001; Krishna et al., 2003) (Figure 1B).

Treble clefs share the unusual geometry of a zinc binding site formed by four ligands, two of which are

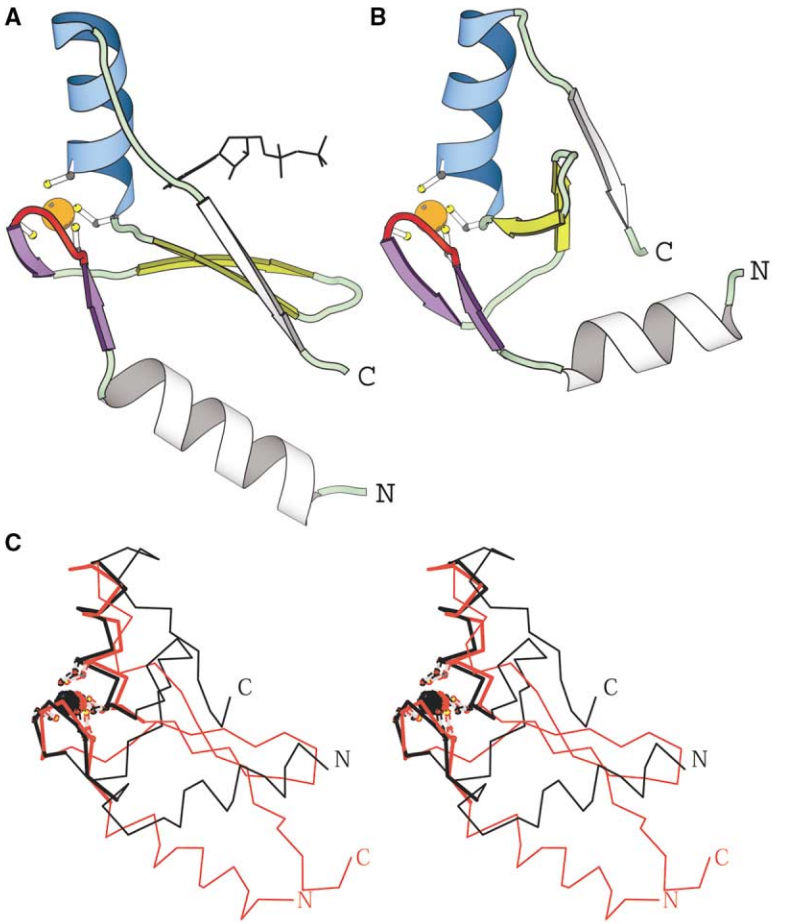

Figure 1. Diagrams of ANBP and ARF-GAP Domain

(A and B) The structural diagrams of (A) ANBP (1uw1) and (B) Pyk2-associated protein β ARF-GAP domain (1dcq) are shown. 1uw1 is an isolated folding unit and 1dcq is a domain within a larger structure with which it has stabilizing intramolecular interactions. In both figures, the N-terminal β-hairpin is purple, the zinc knuckle is red, and the C-terminal helix is cyan. The β-hairpin between the N-terminal zinc knuckle and the C-terminal helix is yellow. All other secondary structure elements that do not contribute to the core of the treble clef finger are white. The side chains of the zinc-chelating residues are shown in ball-and-stick representation, and the zinc atom (orange) is shown as a ball.

(C) Stereo diagram of the structural superposition of ANBP (1uw1, red) and the ARF-GAP domain (1dcq, black). The structures were superimposed using the program insightII by manually defining equivalent residue pairs (1dcq_A: 262–268, 282–294; 1uw1_A: 21–27, 44–56, shown as thick lines). All figures were made using the program BOBSCRIPT (Esnouf, 1999).

contributed by an N-terminal β-hairpin (knuckle) and the other two from the first turn of an α helix. The knuckle (purple) is connected to the α helix (cyan) by a β-hairpin (yellow) (Figure 1B). The structural similarity of ANBP to treble clef fingers is remarkable and residues from the zinc binding region of ANBP superimpose with a RMSD of 1.21 Å (160 backbone atoms from 20 residues) to the treble clef finger (Pyk2-associated protein β ARF-GAP domain) shown in Figures 1B and 1C. The side chain orientation of the zinc-chelating residues and the geometry of the zinc binding site of ANBP are strikingly similar to those of natural treble clef fingers. It is likely that the zinc ion in ANBP plays a structural rather than a functional role (Lo Surdo et al., 2004) similar to those of treble clef fingers (Grishin, 2001; Krishna et al., 2003). Also, treble clef fingers generally develop the functional site around the α helix (cyan) (Grishin, 2001). Interestingly, the key residues of the nucleotide binding site in ANBP are contributed by the C-terminal α helix as well (Lo Surdo et al., 2004) (Figure 1A). Thus, there is a significant structural similarity between ANBP and naturally occurring treble clef finger proteins. Since in vitro generation of ANBP is independent of natural evolutionary processes, ANBP cannot be homologous to treble clef proteins and thus represents a structural analog of any treble clef finger.

It is important to have experimental proof of analogy. The structure of ANBP shows that the possibilities in stabilizing small (~80 residues) proteins are rather limited and have been probed thoroughly by nature. It is remarkable that a small randomly synthesized protein selected for ATP binding developed a core of a treble clef finger, which is commonly found in many proteins. The in vitro translation of the evolving proteins took place in the presence of rabbit reticulocyte lysate, which contains zinc at micromolar concentration (Keefe and Szostak, 2001). However, as far as we can tell, there was no selection force in the experiment by Keefe and Szostak that would specifically mold the zinc binding region of ANBP into a treble clef; i.e., the protein was selected for ATP binding and not for zinc binding. An unexpected and convergent appearance of the treble clef motif suggests that there are a limited number of ways to chelate the zinc ion. The remarkable structural similarity between ANBP and treble clef fingers that extends over the ligand binding site urges caution in inferring homology based only on structural similarity and the presence of similar ligand binding sites. The whole structure of ANBP forms an isolated folding unit, and it is not known whether the treble clef motif constitutes its folding nucleus (Lo Surdo et al., 2004). Generally, the task of identifying remote homologs in the protein world remains difficult and controversial. Homology is typically inferred by sequence, structural, and functional similarities (Murzin, 1998). On the other hand, analogy cannot be directly argued for and thus is inferred by the lack of homology. A number of studies (Matsuo and Bryant, 1999) have explored different discriminators between homologs and analogs. However, the largest difficulty here is to assemble a set of analogs, since it is difficult to distinguish analogs from remote homologs. Proteins like ANBP could provide first examples of true structural analogs.

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A Novel Approach to High-Throughput Screening: A Solution for Structural Genomics?

A quasi in situ technique for screening of diffraction quality biomolecular crystals presents itself to revolutionize the crystallogenesis field.

For decades structural biology has been key to the understanding of the role of biological molecules in the living cell. To date 85.3% of structures deposited in the Protein Data Bank have been determined by X-ray diffraction crystallography. As the name crystallography suggests, this method absolutely requires the preparation of crystals, a task that is challenging and time consuming at times. Today much of the effort that goes into the determination of the 3D structure of a biological molecule actually goes in finding the ideal growth conditions and obtaining the crystals.

Unlike inorganic or small organic molecules, biological molecules are quite complex and present distinctive physicochemical properties. Therefore, the crystallization process of these molecules depends on a much larger number of parameters including pH, temperature, protein concentration, nature of the solvent and precipitant used, and purity, not to mention biological contaminants (for a detailed discussion, see Ducruix and Giege [1991]). There are few rules and little guidance available to explain how to crystallize a new macromolecule. With rare exceptions the phase diagram of these complex biological molecules is unknown. Several methods, batch, vapor, counter diffusion, and their variations, are available to the crystallographer. Among these the vapor diffusion method is the most popular and mostly employed by the automated crystallization trials. In fact, current crystallization procedures can be broken down into two stages: "screening," in which various experimental conditions are tried, and "optimization," wherein the quality and size of the crystals are improved (Chayen and Helliwell, 1998). To address the first stage, structural genomic and proteomic projects have been leading the development of high-throughput automated crystallization stations that can prepare hundreds of experiments. These "brute force" crystallization stations are usually equipped with automated microscopes as their only diagnostic tool and, although many times successful, reliable production of diffraction quality crystals that can yield atomic resolution structural information has been limited.

The automated analysis of vapor diffusion crystallization drops with X-rays proposed by Jean-Luc Ferrer's group is a novel approach to the diagnostic problem and the production of diffraction quality crystals. The authors demonstrated that it is possible using the vapor diffusion method and standard crystallization plates (see http://www.hamptonresearch.com/support/pdf101/greiner.pdf) to screen for best crystallization conditions and even determine the 3D structure with X-ray diffraction without removing the crystals from the crystallization drop. One of the main disadvantages in the current configuration of the method is that the plates must be moved from their usual horizontal position into a vertical configuration for the X-ray diffraction analysis. Although the authors used small drops and small reservoir volumes to help with the stability of the drop during the rotation process, the actual effect of the rotation on the shape of the drop and the crystals is not clear. It is also possible that if the crystals are floating in the drop they will move during data collection and it would be impossi-