Aim 2: **Trait-to-gene network module discovery pipeline**

**Rationale**: We propose to develop and implement methods to build gene networks from co-expression data on multiple crop species to identify genes that are potentially central to a particular trait of interest. We will then test candidate genes by over-expression, knock-outs, and knock-ins in Arabidopsis.

**Novelty**: The trait-to-network module approach follows the spirit of AraNet [Lee 2010] and PlaNet [Mutwill 2011] in that multiple species are used to identify functionality in gene networks. What is novel in our proposed approach is: (i) we use expression data from trait-relevant experiments on multiple crop species to “weight” edges in the network and identify sets of genes associated with a trait, (ii) we identify orthologous genes that are relevant to a trait, some of which may be missing in Arabidopsis, and (iii) our experimental strategy is based on a medium throughput validation testing in an inducible expression system in Arabidopsis.

**Significance: Agronomic traits and phylogenomic context**: Since the dawn of agriculture, farmers and scientists have improved crops by selection and breeding. Now that many crop and non-crop species have been sequenced, these species can be related through phylogeny Fig. X. Among the 21 sequenced species in the tree, the crop species lie at phylogenetic distances of a hundred million years or more from a common ancestor [Chaw et.al. 2004]. Nevertheless, there is evidence for conservation of specific gene functions across these species, sometimes at large phylogenetic distances [Irish and Yamamoto 1995]. As such, complex agronomic traits, such as seed development, seed composition, root architecture, flowering time etc., likely result from medium-sized conserved networks of genes rather than single genes [Espinosa-soto et al., The Plant Cell Nov 2004, To et al., The Plant Cell July 2006]. Arabidopsis, through its amenability to mutational and transformational studies, has provided the vast majority of knowledge about these traits, e.g. flowering time [Espinosa-soto et al., The Plant Cell Nov 2004], seed development [To et al., The Plant Cell July 2006] and root architecture [Péret et. Al., Trends in Plant Science July 2009]. Because Arabidopsis has limited tolerance to extreme conditions, data about environment-specific responses of genes is easier to obtain in other species [Li et al. 2011, Tuteja et al. 2010]. Examples include drought resistance [Shen Y, Venu RC, Nobuta K, Wu X et al. 2011] and early seed development [http://www.ncbi.nlm.nih.gov/geo/ : GSE29163]. In addition, expression atlases exist for each of several crop species [Severin et al. BMC Plant Biology2010].

**Gene Discovery**: The combined computational-experimental approach described below, capitalizes on mining genomic data from crop species, to inform the identification of gene network modules in Arabidopsis associated with traits of agronomic interest. This will lead to novel gene discoveries that can be tested using Arabidopsis as a model. For example, in some cases, this comparative network analysis will identify Arabidopsis orthologs of crop genes, whose significance in the trait could not have been identified based solely on Arabidopsis data. In other cases, it will identify nodes of networks that are “missing” in Arabidopsis, but present in the crops. These crop genes could be “knocked-in” to Arabidopsis, using a protoplast transient assay system we describe in Aim 2B. Here is the method:

**Step 1**: **Identify** **trait-related expression datasets**: For each trait, collect one set of experiments [NCBI GEO] that are relevant to the trait (e.g. during seed development). Collect a second set of expression data under unrelated conditions. Genes that do not show variation, as determined by a minimum variance cut-off across all experiments are “housekeeping” genes, and are removed from further analysis. Further filters are applied to remove poor quality data (e.g. low counts). After filtering, raw counts are normalized using a full-quantile normalization method [Bullard et.al. BMC Bioinformatics 2010].

**Step 2**: **Compute gene correlations**: Build gene correlation networks separately in each of species S1…Sn. We will use methods for correlation proven useful in other plant network tools including Pearson correlation coefficient [Usadel et. al., Plant, cell and environment, 2009],as well as cosine coefficient (CoP) [Ogata et. al., Bioinformatics 2010] and Mutual rank [ATTEDII, PlaNet] [Obayashi et.al., NAR 2008; Mutwil et.al., Plant cell, 2011] and test other correlation methods discussed in Aim 1. A gene correlation network (CNi) for species Si consists of edges {g1, g2}, provided the absolute value of the correlation between these two genes is at least 0.5 with p-value <=0.05

**Step 3. Consensus through “weighting” of nodes and edges:** Each gene g, from a specific species network that passes an orthology cutoff (Stringent BLAST e-value cutoff) (Kranthi- where is this cut off determined?) with respect to some Arabidopsis gene g’, will give g’ a “weighted” value. Thus g’ may receive “weight” values from several genes in each network, and from multiple species networks. Further, the gene g in one network, may add to the “weight” for nodes or “edges” of several gene pairs in Arabidopsis as shown in Fig X. If g is not orthologous enough to any gene in Arabidopsis, but is orthologous enough to genes in other crop species, then we consider that gene to be a candidate for a “knock-in” experiment in Arabidopsis. If there is an edge between g1 and g2 in a species-specific network, and g1 exceeds the orthology cutoff to g1’ in Arabidopsis (as does g2 with respect to g2’), then add a “weight” to the edge between g1’ and g2’. Experimentally validated edges from Arabidopsis provide additional weights to the network edges and nodes. Edges representing predicted Cis-binding sites for Arabidopsis transcription factors, are added to provide confidence and direction to the regulation network. The final network including nodes and edges, with assigned weights, forms the Treturn network within Arabidopsis

**Step 4**: **Identify conserved network modules**: The reciprocal of the weights of the edges form a measure of distance, thus assigning low distance to genes that have often been associated together. Next, we perform k-means clustering or possibly affinity propagation clustering [Frey and Dueck, Science 2007] based on this distance measure. Candidate clusters may be ranked based on the median “weight” count for the nodes, the mean thickness of edges, or edge density.

**Step 5: Mutant studies in Arabidopsis**: Identify genes central to each network module, and prioritize genes that are poorly characterized in (or even absent from) Arabidopsis. Mutagenize those genes by creating knock-out mutants, “knock-ins” (of the missing gene), or over-expression lines. This is explained further in Aim 2B.

**Dealing with potential Orthology and Paralogy issues**: By collecting weights supporting nodes and edges from multiple species, the “weighted” network includes all paralogs across species. Because the propagation of edges between all pairs of orthologs may inflate the weight assigned to some pairs of paralogs, we will explore methods to prioritize genes for phenotypic assays by ranking the genes within a network module based on the average number of paralogs and/or gene family members across the species.

**Proof-of Principle Preliminary Analysis:** To test this approach, we use seed development as the trait of interest [Baud and Lepiniec, Progress in lipid research, 2010]. In Arabidopsis, LEC1, LEC2, FUS3, ABI3 and ABI5 are known master regulators of seed development, and likely exert important influence on early stages of seed nutrient accumulation [Santos-Mendoza et. al.2010. The seed trait has been studied in multiple species, and ample mutant phenotype information is available for *in silico* validation of our network predictions [Meinke D et. al., Trends in plant sciences 2008].

**Construction of gene correlation networks**: We have used deep transcriptome data sets from early seed tissue samples of Soybean and Maize to perform this preliminary analysis [NCBI GEO] [REF]. Following the specifications of the first two steps above, we found CNsoybean and CNmaize . Then, we assigned orthologs to Arabidopsis and each other (Kranthi- what do you mean by “each other”? Soy and Maize? Unclear). For this preliminary work, orthology was assigned based on best reciprocal BLAST matches. More sophisticated approaches to orthology assignment will be used in the final work, as discussed above in Aim 1. This unified network contains XX nodes (YY genes) and ZZ edges.

The distance between nodes, computed as the reciprocal of edge weight [REFERENCE], was used to cluster the nodes. This distance matrix was subjected to k-means clustering to identify conserved clusters of co-expression [REFERENCE].

REST OF THE PRELIMINARY RESULTS WILL DEPEND ON THE RESULTS OBTAINED AT THIS STAGE. WE ANTICIPATE THAT LEC1, LEC2, FUS3, ABI3 AND ABI5 GENES WILL BE REDISCOVERED IN ADDITION TO OTHER GENES THAT INTERACT WITH THEM.

IF ANY UNANNOTATED GENES APPEAR IN THE NETWORK WE CAN FOCUS ON THOSE FOR CAREFUL ANNOTATION TO IDENTIFY POSSIBLE ROLES. ANY GENES MISSING INARABIDOPSIS ARE OBVIOUS CANDIDATES FOR KNOCK-IN STUDIES. SUCH “MISSING” GENES WILL BE RANKED BY AVERAGE NUMBER OF PARALOGS ACROSS SPECIES.

**Aim 2B: Experimental Validation Strategy**. In Aim 2A, we develop and test the method for exploiting data associated with traits in crop species, to inform network studies in Arabidopsis, which ultimately will aid in translational studies back to crop. As proof-of-principle, we tested this approach for a trait “seed development” for which there were ample mutant data with which to validate the genes uncovered in our networks. In Aim 2B, we test in Arabidopsis genes important for seed development in crops. We will use a medium throughput dexamethasone inducible transient assay system, to assay transcription factors and identify their targets in vivo [Sablowski and Meyerowits Cell 1998]. For TFs that pass initial validation in this transient protoplast system, we will proceed to stable transformants (e.g. T-DNA, overexpression, or “knock in” for cases where the gene is missing in Arabidopsis).

**Experimental method**: We have developed an approach (named “Network Walking”) aimed at analyzing the network targets of a transcription factor in *Arabidopsis* FACS sorted protoplasts. This rapid approach identifies transcription factor targets in less than a week of experimentation, following methods developed by Bargmann and Birnbaum [Bargmann BO, Birnbaum KD (2009) Positive fluorescent selection permits precise, rapid, and in-depth overexpression analysis in plant protoplasts. *Plant Physiol* **149:** 1231-1239.][Bargmann BO, Birnbaum KD (2010) Fluorescence activated cell sorting of plant protoplasts. *J Vis Exp*.] Using Gateway™technology, we have engineered a vector for which any TF can be fused with a GR (the glucocorticoid receptor) tag. This 35S-TF-GR chimera allows one to i) overproduce the studied TF in the protoplasts, and to ii) control its entrance into the nucleus using dexamethasone (DEX) treatment [Lloyd *et al*, 1994 Lloyd AM, Schena M, Walbot V, Davis RW (1994) Epidermal cell fate determination in Arabidopsis: patterns defined by a steroid-inducible regulator. *Science* **266:** 436-439.][Sablowski and Meyerowitz, 1998 Sablowski RW, Meyerowitz EM (1998) A homolog of NO APICAL MERISTEM is an immediate target of the floral homeotic genes APETALA3/PISTILLATA. *Cell* **92:** 93-103.] [Bargmann BO, Birnbaum KD (2009) Positive fluorescent selection permits precise, rapid, and in-depth overexpression analysis in plant protoplasts. *Plant Physiol* **149:** 1231-1239.][Bargmann BO, Birnbaum KD (2010) Fluorescence activated cell sorting of plant protoplasts. *J Vis Exp*.]. We recently succesfully used this “network-walking” approach (FACS assisted protoplast selection + DEX fusion) to study network targets of the well-studied TF, ABI3 [Bargmann et al 2012, In Preparation].

Sentinel genes predicted to be targets of the TF (based on the “weighted network”) in seed development, will be assayed by Q-PCR, to ascertain any affect this gene might have on their steady state expression levels. A transcription factor that significantly changes the expression level of one or more sentinel genes is assumed to be involved in the regulation (direct or indirect) of that gene. Positive results will be followed up with: (i) transcriptome responses in the protoplast system, and (ii) *in planta* experiments in Arabidopsis (e.g. T-DNA mutants, overexpression) as well as “knock ins”, for genes not present in Arabidopsis. The approach of identifying regulatory hubs, was highly successful in identifying master regulatory genes in N-usage in Arabidopsis [Gutierrez et al 2008] Similarly, this “weighted network” approach, which is fueled by gene correlation networks in crops, will enable us to target genes for study in Arabidopsis with high potential for translational impact in crops.