# The Flavor Network

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**Abstract**

The authors investigate regional variations in culinary culture by constructing a flavor network of food ingredients, based on shared flavor compounds, and comparing this network to recipe data. They show that Western and Eastern cuisines differ in their compound sharing patterns. The findings show, in particular, that only Western cuisines support the hypothesis that foods sharing flavor compounds are more likely to taste well together. Using additional data the authors investigate the validity of this hypothesis further and suggest a new, more specific version of the hypothesis, which holds for a particular subset of compounds.

*Keywords:* food, network, flavor compounds, food choice, food culture, gastronomy

Food lies at the center of our life [1-3]. Human beings are omnivorous and are the only species to have developed a highly complex and diverse food culture. This raises an interesting question: *How much of our culinary variety is due to cultural influences and how much due to innate preferences?*

This question has been the subject of extensive research, which has brought to light a number of universal principles that govern our food choices. For instance, sweetness and fattiness are clear favorites across cultures because they indicate the presence of carbohydrates and fat, both of which are good energy sources [4,5]. There are also other types of regularities that are functions of the climate in which foods are produced and consumed. For example, the usage of spices is very heterogeneous across cultures. A study revealed that the use of spices in a given region is highly correlated with its annual temperature, as well as with the usage of meat (which is more perishable in certain regions) [6,7].

It nevertheless remains unclear whether there are further principles that underlie our food culture. One interesting candidate is the "*food pairing hypothesis*" originally proposed by François Benzi and Heston Blumenthal, which later gained considerable interest among chefs and scientists [8]. The hypothesis is the following: "If two ingredients share important flavor compounds, then they will go well together". Numerous pairings have been created using this principle such as dark chocolate and blue cheese, pork and jasmine, white chocolate and caviar, etc. However, the evidence for this hypothesis has been anecdotal and has not relied on systematic and quantitative investigation.

We recently introduced the "flavor network" (Fig. 1) as a step towards a more systematic validation of the hypothesis and also as a framework for further study of food choice [9]. The Fenaroli's handbook [10] that lists the natural occurrences of flavor compounds provides us with a network of flavor compounds and culinary ingredients, from which we can derive a network of culinary ingredients (the flavor network) in which connections between ingredients signify shared compounds. Combined with recipe data from multiple online recipe datasets (two from US and one from South Korea), we showed that shared compounds affect ingredient combinations very differently in Western and Eastern cuisines. North American recipes for instance have ingredient combinations that share many flavor compounds much more frequently than randomly generated recipes with the same usage frequency of ingredients. By contrast, East Asian recipes tend to share fewer flavor compounds than their randomized versions. These datasets allow us to extract authentic ingredients (and authentic combinations) of each cuisine and put them in perspective.

More recently we have collected further data sets to investigate the shared compound hypothesis more deeply. These include a compound-ingredient association data set known as the VCF (Volatile Compounds in Food) database [11], to which we were kindly given access for research purposes by the company TNO. The VCF database contains the concentrations of many compounds in foods, which goes further than the mere presence or absence of compounds recorded in the Fenaroli database. A second dataset we have analysed is The Flavor Bible [12], which is a curated list of almost six thousand ingredient pairings recommended by chefs. This dataset focuses entirely on flavor pairings, whereas the recipes used in our earlier analysis also contain many ingredients that contribute to the structure and texture of a dish, rather than its flavor. A third dataset are descriptions of the odor and flavor of chemical flavor compounds by food scientists, which are part of the Fenaroli handbook. We can test the shared compound hypothesis using the Flavor Bible and the VCF database by randomizing the former and testing whether more compounds are shared between ingredients in the original pairings than in the randomized version. The concentrations of the VCF database allow us to impose minimum concentration thresholds on the compounds we consider, and the flavor descriptions allow us to further filter the compounds according to their flavor or odor. Considering all compounds, the original Flavor Bible data differs from randomized versions by one-and-a-half standard deviations. If we only consider compounds that mention foods in their flavor descriptions, i.e. compounds that have food aromas, this rises to two-and-a-half standard deviations. And if we only consider compounds that appear in concentrations of 100 parts per million (ppm) or higher, then the significance rises further, to almost four-and-a-half standard deviations. This indicates that the shared compound hypothesis may hold particularly for dominant foods with flavor compounds that have food aromas.

Our work can be seen as part of a greater movement, which sees the application of data mining and network analysis approaches to the social sciences, arts and humanities. In the past two decades these methods have become an important research tool in the biological sciences, resulting in completely new biological disciplines, such as systems biology and computational biology. From there they have started to spread to other areas, such as linguistics [13], archaeology [14], and art history [15]. The research we present here represents an application of large-scale data analysis to gastronomy and food science, and we hope that this might form a contribution to the emerging field of *computational gastronomy*.

**References and Notes**

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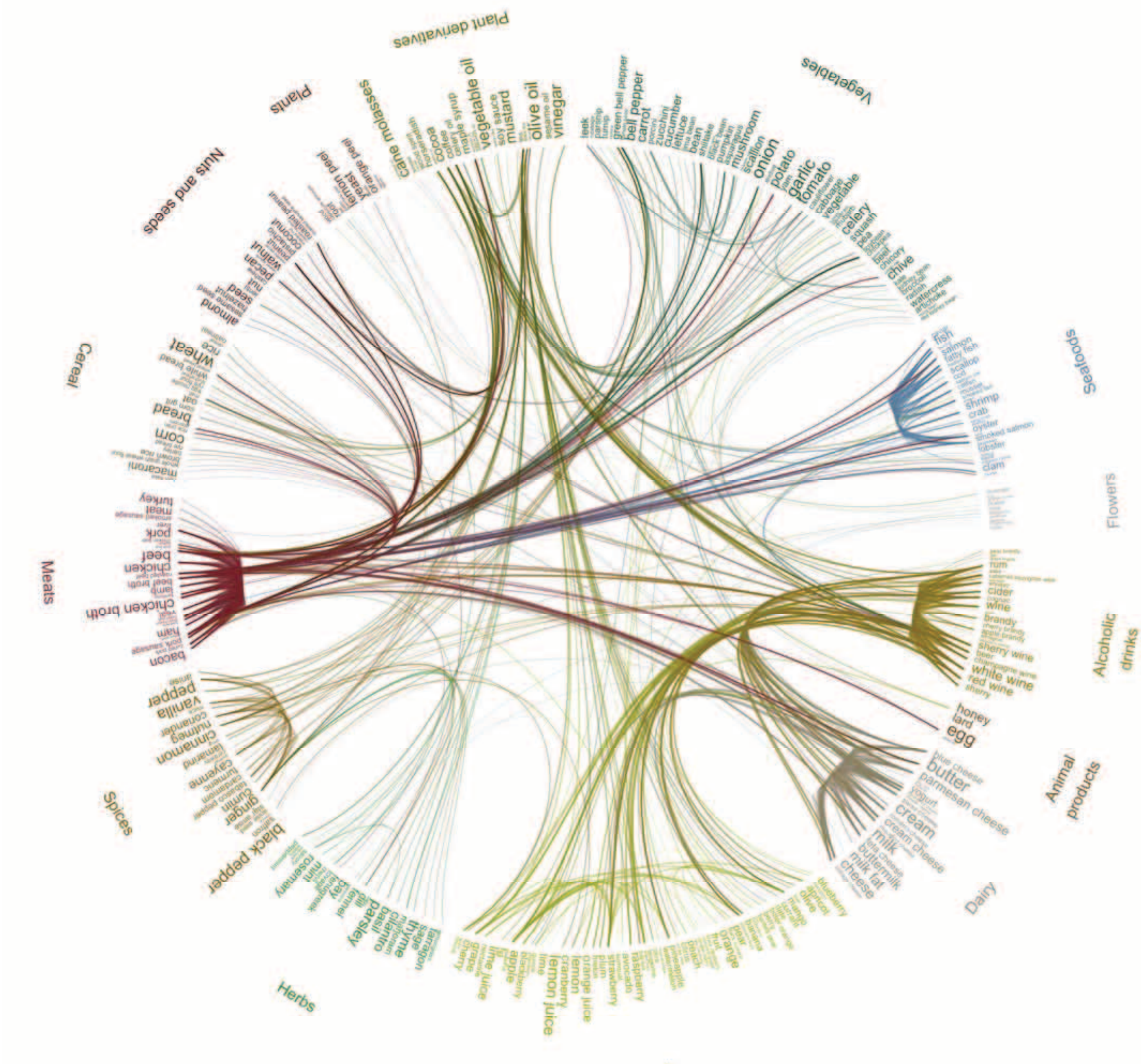


**Figure 1: Weighted network of food ingredients derived in [9] from the bipartite network of ingredients and chemical flavor compounds. The thickness of connections between ingredients reflects the number of compounds shared between them. Chefs and food scientists have hypothesized that an increased number of shared compounds is an indicator of the flavor compatibility of two ingredients in food preparation. (© Yong-Yeol Ahn)**

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