The presence of 'rich clubs' is a matter of distance in networks

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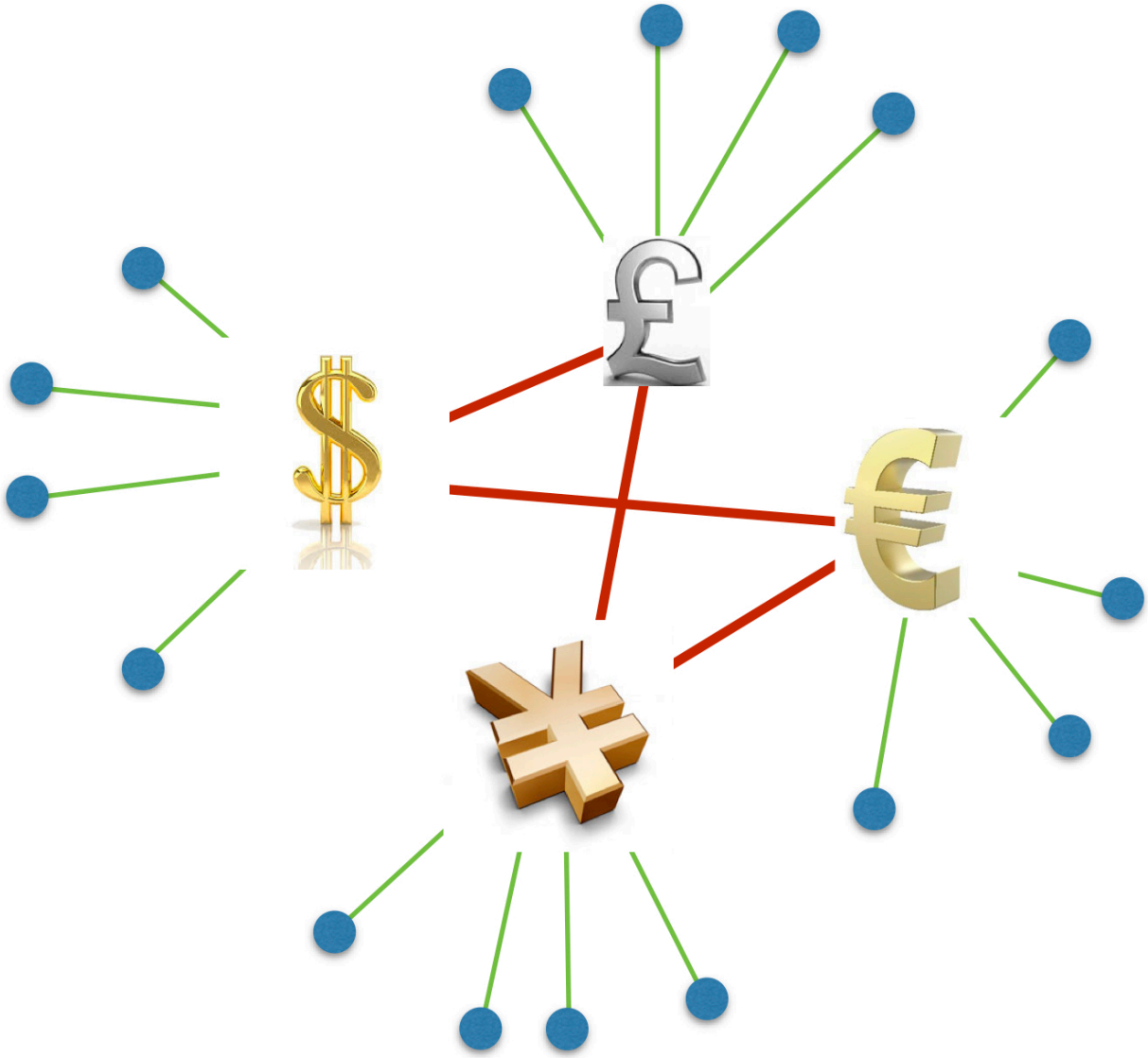

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Recent research has revealed that during growth/evolution of networks, the emergence of "rich clubs," which are formed by high-degree hubs that are interconnected to each other more densely than expected, can be simply a matter of distance. The members of the club can easily utilize each other's spread-out system of connections.

"The rich club phenomenon seems to be a divisive property in complex networks. There are numerous networks showing similar small-world properties, high clustering and power law degree distribution, but with completely different 'rich club' characteristics," noted András Gulyás, leading scientist of the research team.

Until recently, there were no results in the literature that revealed the reasons behind the presence or absence of rich clubs, or grab the 'rich club' dynamics in growing/evolving networks. "Our model is a remarkable indication that very different rich club characteristics can be put into a common evolutionary perspective so we can better understand network formation mechanisms influencing the 'rich club' property," said Dr. Gulyás regarding the significance of the results. The study is published in *Scientific Reports*.

An interesting aspect of current study is that it comes from the field of computer networking. The researchers created a non-Euclidean geometry-based network growth model in which new nodes can connect to a given number of the closest nodes. However, direct connection can only be possible within a limit of distance, above which a "bridging" node is required to establish the new connection. Analogously, in many real networks there can also be different distance-related burdens in setting up connections. For example, in power grids, the transmission of electric current through longer distances is efficient only with transformations at middle stations.

Similarly, in certain social networks, middlemen as intermediate bridges may play a crucial role in enhancing cooperation between individuals. In the internet, higher-level service providers can act as bridge nodes connecting the customer cones of their subordinate lower-level providers, but the geographical distance in this case is less influential. By contrast, in case of airport networks, it seems that very long-distance connections are more frequent than in the case of the power grid or the internet. The very different rich club structure of these networks can be replayed by adjusting the single geometrical limit in the model. Even the complete absence of rich clubs in protein-protein interaction (PPI) networks can also be recovered. The lower the distance limit, the sparser the connectivity between the club members.

One may speculate as to whether there is a consequence of these results on the strong rich club organization of the human brain. "In our evolutionary model, first the longer distance connections are established if the geometric limit enables them, thus forming the skeleton of the rich club. The rich club skeleton is then extended by shorter, regional connections." In the human brain, something similar happens. The rich club of interconnected cortical hubs is already present by 30 week of gestation. Then the connections between these prospective hubs and the rest of the brain develop until birth. "In the hidden geometry of the brain, the distance limit seems to be large enough to allow the formation of an expensive rich-club core," conjectured Professor Bíró.

More information: Máté Csigi, Attila Kőrösi, József Bíró, Zalán Heszberger, Yury Malkov and András Gulyás *Scientific Reports* (2017) DOI: 10.1038/s41598-017-01824-y The paper is freely available online at www.nature.com/articles/s41598-017-01824-y

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