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A Grand Unifying Theory of Hybrid Life-Cycle Assessment

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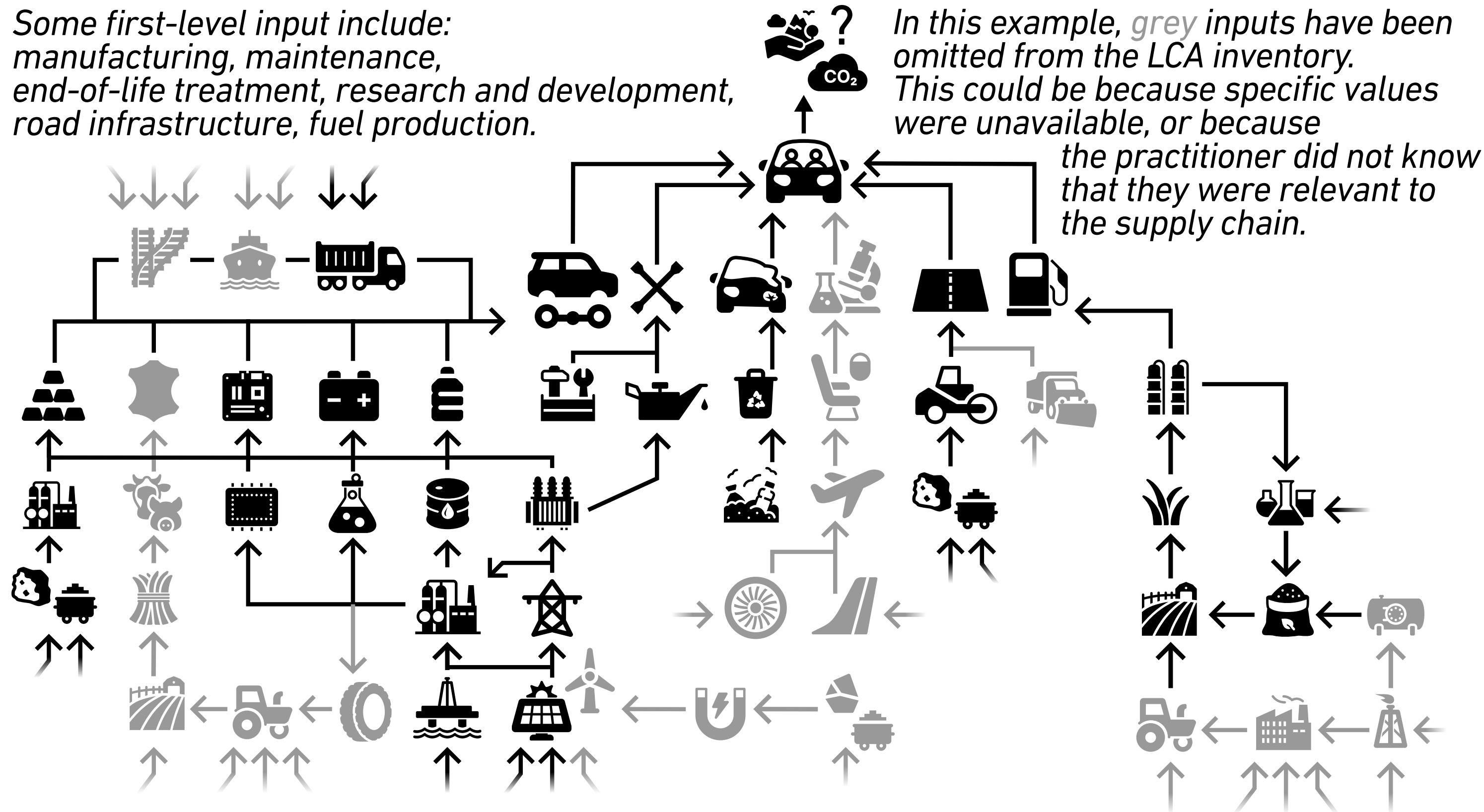
MOTIVATION

Life-cycle assessment (LCA) is a standardized method to calculate the environmental burdens associated with the production of goods or the provision of services. Obtaining accurate LCA results is no longer a purely academic requirement. The method forms the basis of all environmental impact assessment studies that guide policy decisions about present and future technologies. Even more acutely, LCA results are used to determine the amount of carbon-emission taxes levied on economic activities.

INTRODUCTION

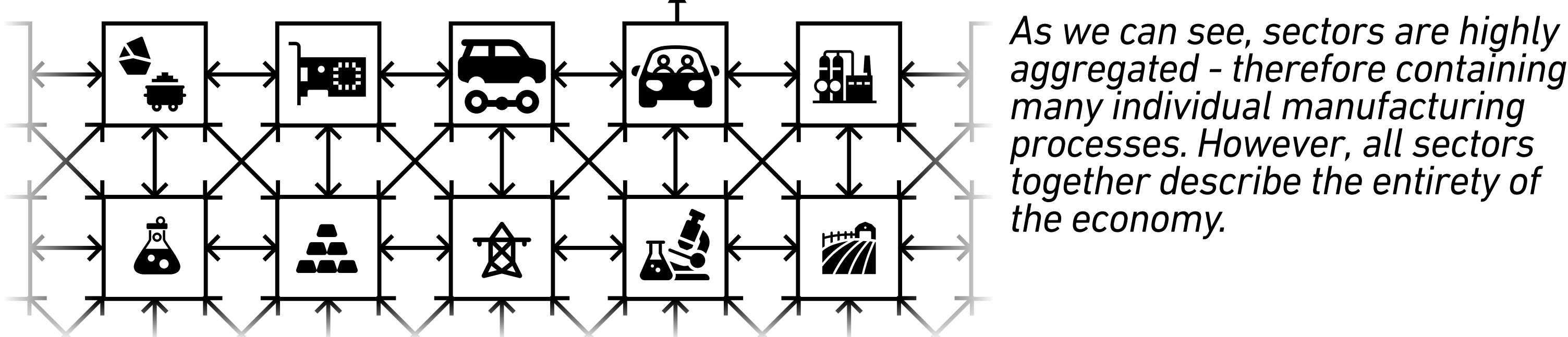
One way to conduct an LCA study of a product or service is to determine the emissions of all relevant upstream production processes [1]. Unfortunately, the complete supply chain of any product is practically infinite - and often very complex. Production processes often depend on each other in circular patterns. Consider, for instance, the example of a simplified supply chain related to automotive passenger transport with bio-fuels:

Some first-level input include: manufacturing, maintenance, end-of-life treatment, research and development, road infrastructure, fuel production.



As we can see, collecting data on all upstream processes of the supply chain is a monumental task. In general, we can not be sure that we did not miss any relevant inputs.

Another way to conduct an LCA study is to instead use data from "input-output" tables, which quantify the economic (=monetary) flow between different sectors of the economy during one year [2]. These tables are regularly published by national governments and international agencies. We can also use this sectoral data to describe the manufacturing process of a car:



Hybrid LCA (HLCA) is the combination of data from a process inventory (highly detailed, but incomplete) with data from input-output tables (highly aggregated, but complete) to capture the complete effort of the economy associated with production of goods or the

HISTORICAL DEVELOPMENT IN HYBRID LIFE-CYCLE ASSESSMENT

Four different methods for HLCA have historically been recognized in the literature [3]:

The "tiered" hybrid method, first proposed by Bullard et al. in 1976/1978 [4] under the term "net energy analysis", simply adds additional demand for the sectoral system. The "matrix augmentation" hybrid method, first proposed by Joshi in 1999 [6] connects the process system to the sectoral system, and removes flows already covered by processes. The "integrated" hybrid method, first proposed by Suh in 2000/2004 [5] operates in the same way. Finally, the "path-exchange" hybrid method, first proposed by Lenzen and Crawford in 2009 [7] changes individual coefficients in the power-series expansion of the A-matrix:

$$\vec{e}_H(\text{tiered}) = \vec{e}_S + \vec{e}_P = \mathbf{B}_S(\mathbf{I} - \mathbf{A}_S)^{-1} \vec{f}_S + \mathbf{B}_P \mathbf{A}_P^{-1} \vec{f}_P$$

$$\vec{e}_H(\text{matrix augmentation}) = \mathbf{B}_H(\mathbf{I} - \mathbf{A}_H)^{-1} \vec{f}_P$$

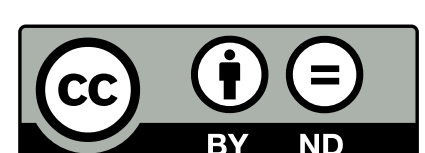
$$\vec{e}_H(\text{integrated}) = \begin{pmatrix} \mathbf{B}_P & 0 \\ 0 & \mathbf{B}_S^* \end{pmatrix} \begin{pmatrix} \mathbf{A}_P & \mathbf{C}_D \\ \mathbf{C}_U & \mathbf{I} - \mathbf{A}_S^* \end{pmatrix}^{-1} \begin{pmatrix} \vec{f}_P \\ 0 \end{pmatrix}$$

$$\vec{e}_H(\text{path-exchange}) = \mathbf{PXC}(\mathbf{B}_S(\mathbf{I} + \mathbf{A}_S + \mathbf{A}_S^2 + \mathbf{A}_S^3 + \dots)) \vec{f}_P$$

Despite a number of recent publications [3], the advantages and drawbacks of these different methods were never conclusively formulated - severely limiting their use.

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UNIFYING HYBRID LIFE-CYCLE ASSESSMENT

We find that the computational structure of all four HLCA methods is the same. While it had previously been observed (without proof) that the *matrix augmentation* and *integrated* method are "mathematically (...) essentially the same" [8, Sec.2.2.1], no such observation has been made for the other methods. Mathematically, the methods can be described using the equation:

$$\vec{e}_H = \begin{pmatrix} \mathbf{B}_P & 0 \\ 0 & \mathbf{B}_S^* \end{pmatrix} \begin{pmatrix} \mathbf{A}_P & \mathbf{C}_D \\ \mathbf{C}_U & \mathbf{I} - \mathbf{A}_S^* \end{pmatrix}^{-1} \begin{pmatrix} \vec{f}_P \\ 0 \end{pmatrix} \quad \begin{array}{l} P \dots \text{process system} \\ S \dots \text{sectoral system} \end{array}$$

\vec{e}_H ... environmental burdens

$$b_{ij} = \frac{\text{burden } i}{\text{output } j}$$

\mathbf{B} ... environmental burden intensity

\mathbf{A} ... technical coefficients

$$a_{ij} = \frac{\text{flow } i \rightarrow j}{\text{output } j}$$

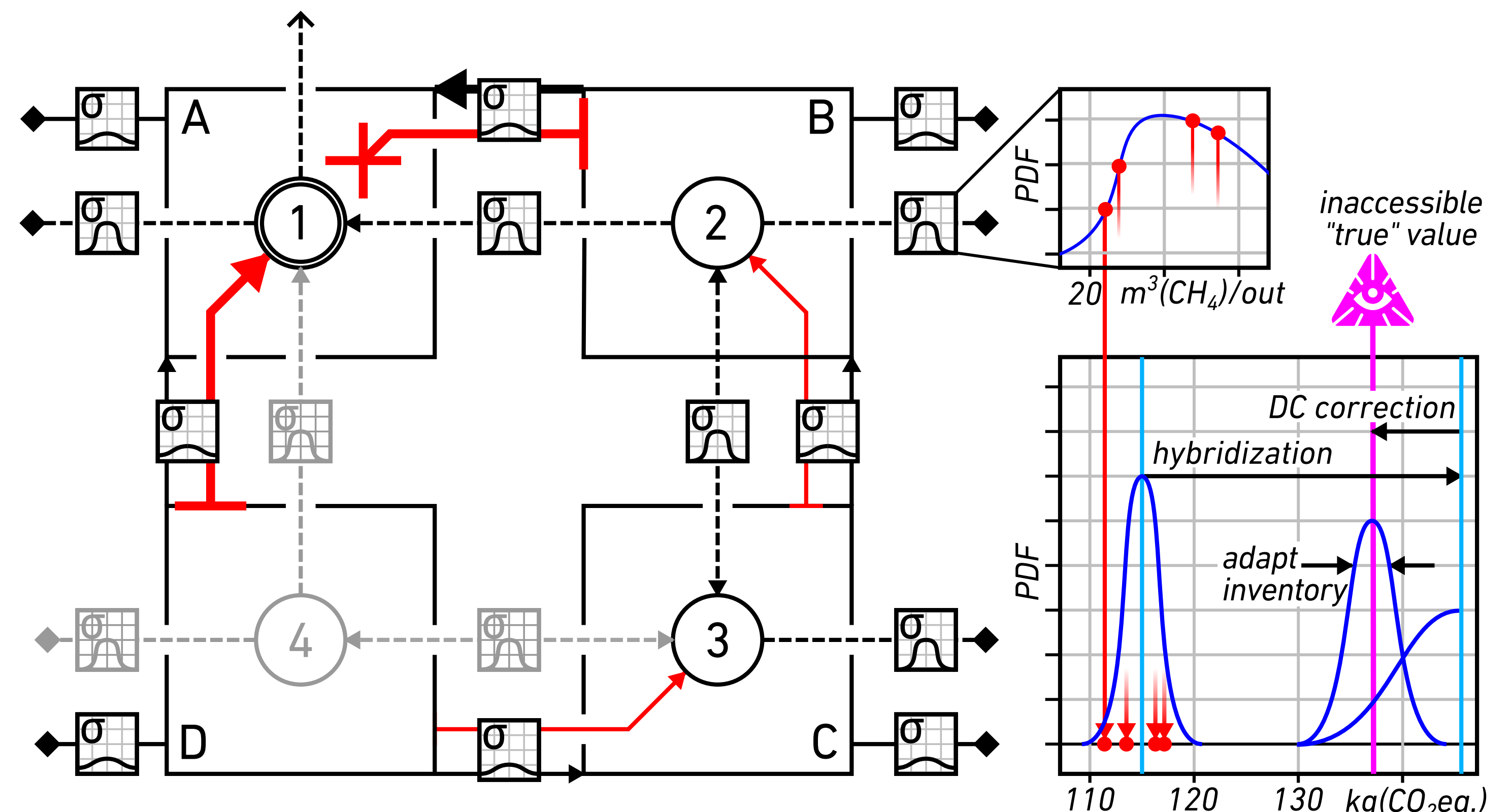
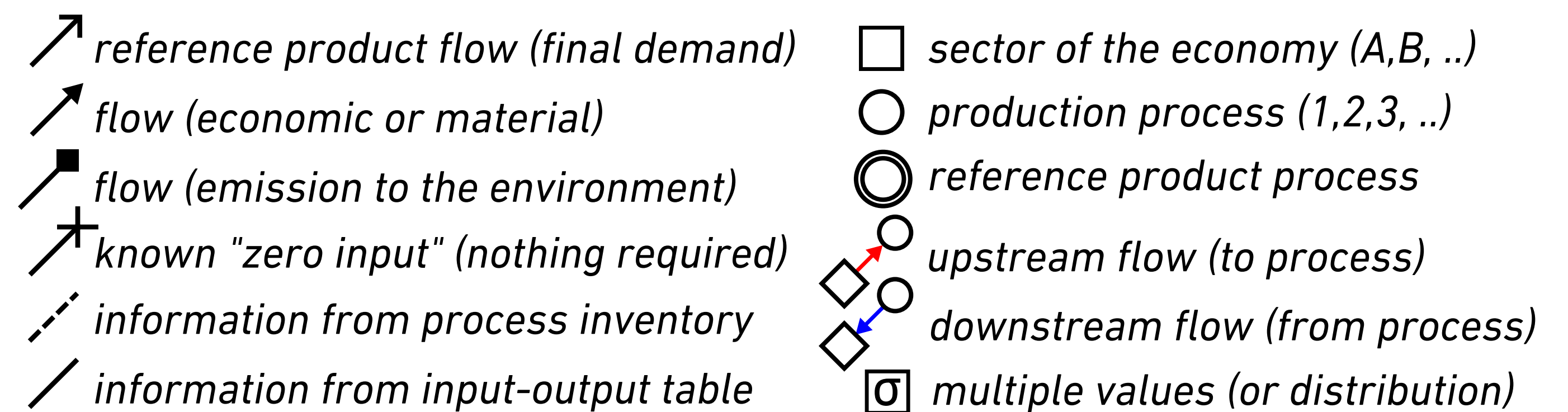
\mathbf{C}^U ... upstream cut-off

\mathbf{C}^D ... downstream cut-off

$$c_{ij} = \frac{\text{flow } i \rightarrow j}{\text{output } j}$$

\vec{f} ... final demand

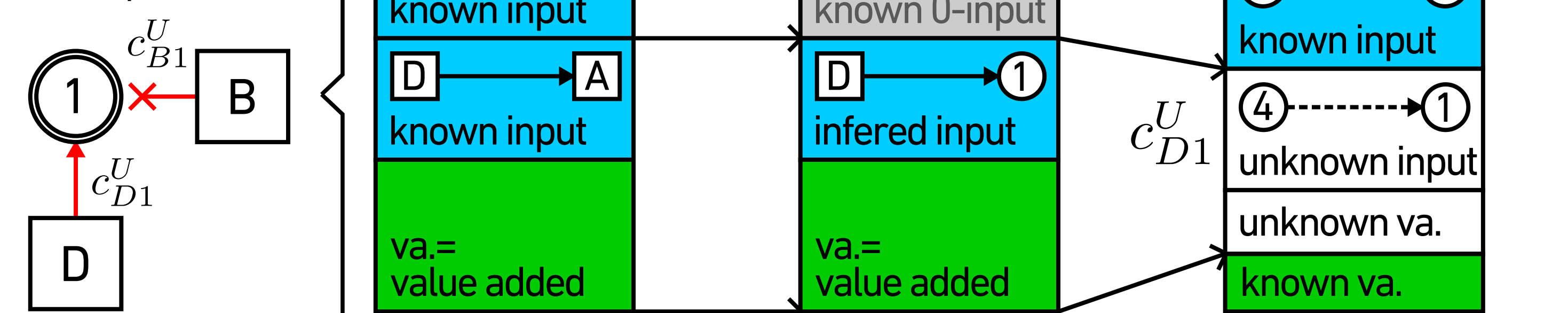
The four proofs range from "trivial" to "rather involved" and use a basis transformation of the underlying vector space and splitting up indices in the power series expansion of the A-matrix. The way in which this equation describes flows between processes and sectors, can also be illustrated using a novel diagrammatic notation:



This illustrates how *upstream flows* and *downstream flows* inter-connect the process system with the sectoral system. Depending on the purpose of the HLCA study, the data origin for the coefficients of the upstream/downstream matrices are different.

If practitioners know how processes are connected to the sectoral system (through sales data for downstream flows and through a bill-of-goods for upstream flows), the matrix can be populated manually. In this case, HLCA is used to solve for "known unknown" inputs. Since that is generally not possible for the background process inventory, these flows can also be inferred from the inherent structure of the input-output table [9]. In this case, HLCA is used to solve for "unknown unknown" inputs:

If process 1 belongs to sector A (etc.), we can use the structure of the input-output table to infer flows. For example:



In order to avoid double-counting of flows (and therefore environmental burdens) from both the process system and the sectoral system, monetary balance must be observed:

$$(c_{(B-2)1}^U x_1 + a_{21}^P x_1) + a_{(A-1)(B-2)}^S x_{(A-1)} = a_{BA}^S x_A \quad x \dots \text{output}$$



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