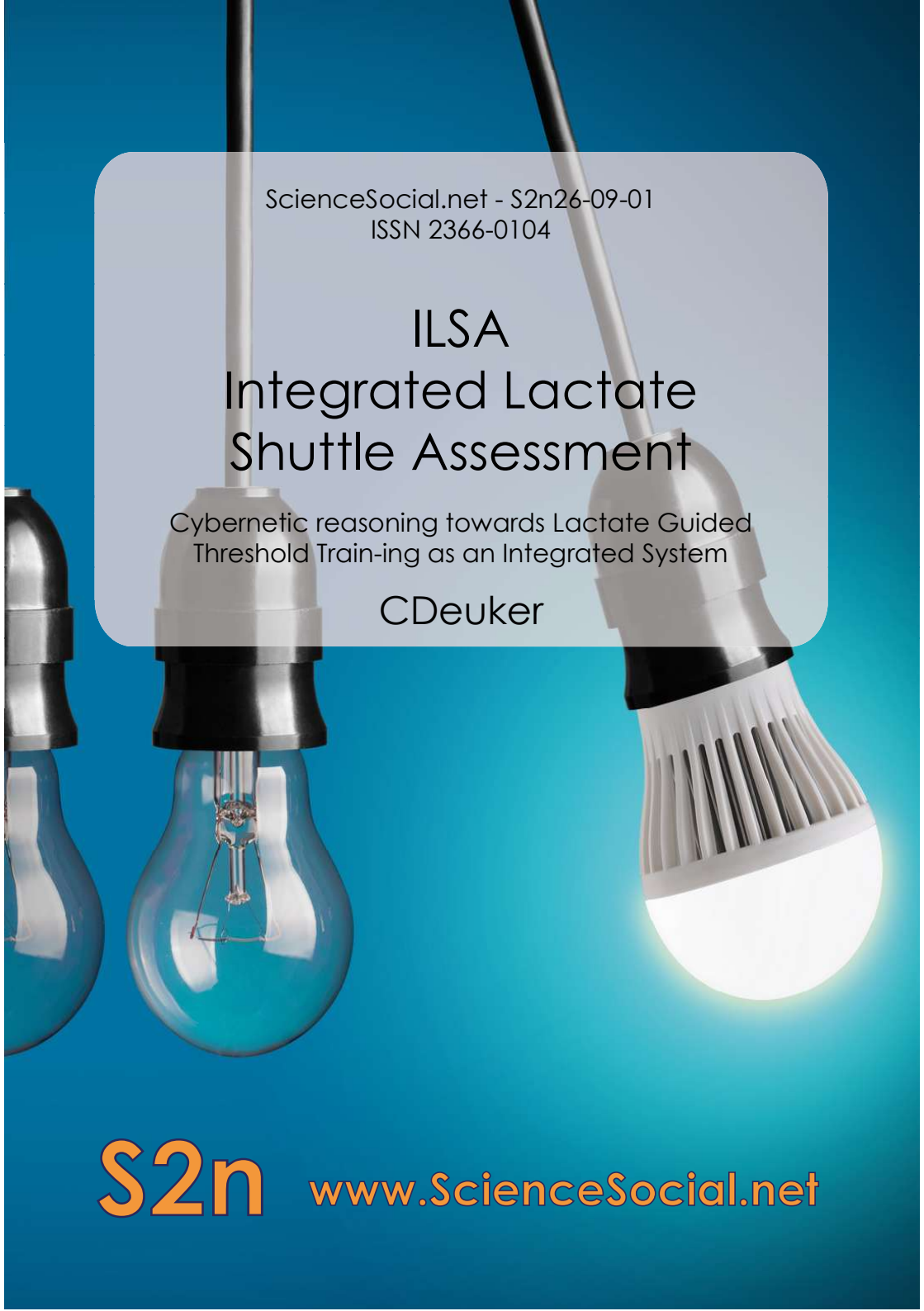




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ILSA Integrated Lactate Shuttle Assessment

Cybernetic reasoning towards Lactate Guided
Threshold Train-ing as an Integrated System

CDeuker

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by

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1 Introduction

Performance in sport is often a combination of different physical skills towards endurance and sprint. Traditional training plans are based on the dichotomy of aerobic and anaerobic energy metabolisms and focus on these different skills in separated realms. Metabolic thresholds operationalize the training impacts for different physical skills by separating the physical requirements of sports into aspects of sprint and endurance. The physiological based dichotomy of aerobic and anaerobic enhances the separation in physical skills and training impacts, with the underlying marginal condition of energy conservation of separated systems.

“Even the traditional distinction between “aerobic” and “anaerobic” glycolysis is conceptually flawed. Glycolysis is a continuous process operating at varying rates regardless of oxygen availability, further highlighting the misconceptions surrounding energy systems ¹.” [Petro, J. L., et al.; 2025; 5].

Training with this flawed concept is then a zero-sum game of sprint and endurance towards an entity of performance.

The lactate shuttle theory shows that energy metabolisms are closer to an integrated system than to a dichotomy towards physical skills [s. Brooks, G. A.; 2020]. Training in sport with a combination of different skills, can benefit by an integrated training with an

¹ Ref. in citation: Schurr A. How the ‘aerobic/anaerobic glycolysis’ meme formed a ‘habit of mind’ which impedes progress in the field of brain energy metabolism. *Int. J. Mol. Sci.* 2024; 25(3) see also: “In this study, conducted on trained human subjects and using magnetic resonance spectroscopy to measure myoglobin desaturation, it was observed that even under conditions of maximal physical effort, a true state of ‘anaerobiosis’ is not reached, as lactate production is not exclusively associated with cellular hypoxia but rather with other metabolic factors, such as increased anaerobic (sic) glycolysis” [Petro, J. L., et al.; 2025; 4].

integrated theory that refers to the entity of performance as well as metabolisms. If you are a sprinter, then you have to focus on the skills of sprint with these special metabolic pathways, keeping in mind that all metabolisms are integrated. With marathon, it's vice versa. For players in soccer or other games, the integration of different physical skills and the focus on the integrated pathways of metabolisms are crucial. The focus on integration in contrast to dichotomic pathways is a conceptual shift from thresholds to shuttles.

„Because lactate, the product of glycogenolysis and glycolysis, is disposed of by oxidative metabolism, lactate shuttling unites the two major processes of cellular energy transduction“ [Brooks, G. A.; 2007; 341–343].

2 Theoretical Considerations

This project takes the numerous scientific insights and papers of lactate shuttle (for a first glance into the literature s. [Deuker, C.; 2017a; 2017b]) as a starting point and not only as a hypothesis. The idea is to operationalize this theory for real training sessions.

“Time is overdue to turn the page on understanding lactate metabolism and consider lactate shuttling as an important component of intermediary metabolism in vivo” [Brooks, G. A., et al.; 2021; 15].

Lactate shuttle gives a new and different view on metabolisms and in a second step in principles of training. As a bridge between different cellular energy sources, lactate stands in the center of an integrated metabolic system.

2.1 System theoretical argumentation to integration

Systems are only stable if they can cope with environmental changes due to their internal processes. They can be defined in all hierarchies, from the universe to the quark even overlapping. A functional setting of environment and system should focus on dominant processes for the description of the specific task. It is possible to define a system of aerobic metabolisms for energy supply in contrast to an anaerobic one. But for the metasystem of locomotion the requests are diverse without a clear distinction towards different energy supply metabolisms. For every step you make, different muscles with different fibers inside are needed. And even every step can be very different in execution. No doubt, all these processes are energy based and especially for locomotion the processes are flexible, which is on the other hand the fundamental idea of training. To preserve locomotion, an integrated energy system is fundamental and the dominant strategy or function of this system. After a sprint, the lion is still behind and you need additional energy to go on.

“But, because of our metabolic plasticity (i.e., the ability to switch among CHO- and lipid-derived energy sources), our endurance capacity is very good by comparison to most mammals, but inferior to highly adapted species such as wolves and migratory birds. Our ancestral ability for hunting and gathering depends on strategy and capabilities in the areas of thermoregulation, and metabolic plasticity” [Brooks, G. A.; 2012; 559].

Evolutionarily this plasticity is the dominant strategy together with energy efficiency towards different metabolic pathways. We are not exclusively born endurance runners or sprinters. We are always born in both realms - more or less- and can develop special tasks.

Locomotion of the body needs a constant energy flux and it is an evolutionary advantage to preserve it. Metabolic pathways for locomotion can be defined as subsystems, but in the end, they refer to the meta-system of the individual and its energy supply system.

From a system theoretical viewpoint, the integration of different metabolic pathways into an energy supply system is crucial. Different metabolic pathways - or the structure of processes - still exist, like aerobic and anaerobic ones, but this dichotomy is dominated by the integration into the metabolic system.

ILSA is not about finding new metabolic pathways or physiological insights, but to look at them from a different perspective of an integrated system. Integration dominates the energy supply system with different structures like aerobic and anaerobic metabolic pathways.

2.2 Practical training constraints towards integration

Every athlete or trainer knows from daily experience, that you can't do always the same. Only pushing to the limit with HIIT won't succeed as well as always zone 2. If you want to expand the limits, you always have to focus on a process and its integration into the system.

The easy day – hard day approach is very familiar to training plans and it shows some kind of integration of session intensity which corresponds in many cases to aerobic and anaerobic metabolisms.

The fundamental idea behind all training plans is supercompensation and every plan has to adopt to it. In order to change structures or processes, you have to set a stimulus that is an unexpected high performance. Only in this situation the system is forced to

restructure the process to cope with future stimuli. The idea of training is based on flexible processes and adaptation of internal structures towards external stimuli. With ongoing stimuli beyond the accepted level no adaptation can follow and overtraining occurs. Planning the intensity of training sessions is the fundamental essence of successful plans, showing the integration of the system with flexible thresholds by integrated processes.

The practical adaptation of supercompensation and its cybernetic theory-based approach is fundamental to all training plans. Flexible thresholds are the result of integrated systems and not of different realms with their specific structure.

3 Shuttles as integrating factors

3.1 Integration between organs

For long time lactate was seen as a dead-end waste product due to a lack of oxygen. This perspective is still widespread in the training of athletes, although science proofed lactate shuttles 40 years ago [s. Brooks, G. A.; 1985; 1986]. Today science found a lot of different lactate shuttles and we know that lactate is used in many ways. Research showed lactate as an energy source in rest as well as in exercise up to 75% of total lactate appearance [s. Brooks, G. A.; 2007; 342].

“Also, working muscle can fuel the beating heart (Gertz et al. 1981), brain (Suzuki et al. 2011; Glenn et al. 2015a; Steinman et al. 2016) and provide gluconeogenic substrates to the splanchnic organs (Bergman et al.; Gerich et al. 2001). Lactate exchanges among muscle, heart, liver and kidneys are obvious examples of lactate

shuttling” [Brooks, G. A., et al.; 2021; 3].

These shuttles show the integration of lactate to other organs, where it is metabolized under aerobic conditions. In this sense the system integrates energy with lactate into different sub-systems or organs.

“Hence, we now realize that lactate produced in working muscle is a major fuel energy source (Stanley et al. 1986; Bergman et al. 1999b), but also that lactate release from working muscle fuels other organs such as the heart (Gertz et al. 1988; Bergman et al. 2009b) and brain (Glenn et al. 2015a) normally, but also in illness and following injury (Marik & Bellomo, 2013; Brooks & Martin, 2014; Garcia-Alvarez et al. 2014b). Moreover, lactate released from working muscles (Stanley et al. 1986; Bergman et al. 1999b) and other driver cells such as the integument is the major gluconeogenic precursor (Stanley et al. 1988; Bergman et al. 2000)” [Brooks, G. A., et al.; 2021; 4].

Out of this perspective lactate is used energetically in a second cycle as an integrating factor of the energy supply system.

3.2 Integration of energy flux with lactate

“Carbohydrate metabolism under fully aerobic conditions relies on lactate shuttling both within and between cells to fulfill various roles (11)², most prominently to provide an energetic substrate for oxidative phosphorylation and to serve as a gluconeogenic precursor” [Emhoff, C.-A. W.; Messonnier, L. A.; 2023; 1].

Lactate shuttle is an integrative factor, not only for different organs,

² Ref. in citation: Brooks, G.A. The Lactate Shuttle during Exercise and Recovery. *Med. Sci. Sports Exerc.* **1986**, *18*, 360–368.

but for the whole energetic system. This integration preserves an energetic flux between situations with varying demands of power supply. For carbohydrate energy fueling, lactate is in the center to cope with disbalances in variable environmental situations.

“Because of the Intracellular Lactate Shuttle, lactate (not pyruvate) is the major fuel for mitochondrial respiration, always and particularly during exercise when the cellular L/P rises and order of magnitude or more (*vide supra*)” [Brooks, G. A.; 2020; 3].

This integration by lactate shuttle is crucial in and between cells of different type and especially vivid in and between muscle cells.

“In sum, the above-cited work shows continuous aerobic (not oxygen-limited) lactate turnover (production and disposal) in humans and mammalian model systems. Further, the work shows two of three features of the lactate shuttle – lactate production in driver cells and disposal in recipient cells and tissues; signaling being a third feature of the lactate shuttle (Brooks, 2000, 2002, 2018)” [Brooks, G. A., et al.; 2021; 4].

3.3 Integration between type 1 and 2 fibers

“Not surprisingly, we now know not only that driver and recipient cells can switch roles depending on conditions, but that some cells can exchange lactate through the interstitium and vascular beds. For instance, during exercise, fast white fibers can provide oxidizable substrate to red, oxidative fibers in the same tissue bed (Baldwin et al. 1972; Hooker & Baldwin, 1979)” [Brooks, G. A., et al.; 2021; 3].

Besides the special and global integration to the energetic system, lactate is prominent in muscle cells. Lactate shuttle between type 2

to type 1 fibers is a crucial energetic integration in muscles for the different processes of the energetic system of locomotion.

“The lactate shuttle includes two key mechanisms: i) The intracellular lactate shuttle, where certain cells (e.g., type I muscle fibers) can oxidize lactate within their mitochondria; and ii) the cell-to cell lactate shuttle, which transfers lactate between cells, such as from type IIX to type I muscle fibers(39, 40)³” [Petro, J. L., et al.; 2025; 7].

Different muscle cells are combined in motor units for an adequate response to locomotion requests. Out of a system theoretic viewpoint, the system reacts with integrated processes on environmental requirements. The combination of different muscle cells and the maintenance of their energy flux is a reaction to environmental stress under scarce energy resources and goal attaining.

4 ILSA – Integrated Lactate Shuttle Assessment

Setting a stimulus that stresses the internal processes is a precondition of supercompensation and can shift the systems capable resources towards energetic, physiological adaption. With a higher workload bigger motor units with stronger muscle cells are utilized according to the Henneman’s principle, and more and more type 2 fibers are working. This adjustment of muscle innervation is a continuous process for locomotion without a previous change in physiological metabolisms. Training, as a shift of homeostasis and

³ Ref. in citation: Brooks GA, Arevalo JA, Osmond AD, et al. Lactate in contemporary biology: A phoenix risen. *J. Physiol.* 2022; 600(5): 1229–1251
Brooks GA. Cell-cell and intracellular lactate shuttles. *J. Physiol.* 2009; 587(Pt 23): 5591–5600

changed probability of future workloads towards locomotion, is based on the integration of different fibers and metabolic pathways through the functions of skeletal muscles. Lactate shuttle between type 2 and type 1 muscle fibers is essential for training. It is an expression of an integrated system and a precondition for supercompensation. An adaptation to environmental stress only can take place with an active integration of different processes in the energetic, physiological system.

The robustness of a system is represented by its capability to cope with environmental stress through its integrated processes. This cybernetic argumentation is crucial for the magnitude of forced power as well as the duration of the environmental stress towards the energetic resources of locomotion. Even if you are only interested in special skills of the system, you should be aware that it is integrated. The reaction of the system to return to homeostasis shows its temporal state to cope with divergent situations.

Lactate shuttle is one crucial integration in the energy system towards locomotion and rising power. It is formed and used in rest and particularly in situations of higher performance.

“In sum, intracellular lactate disposal is accomplished by a transport mechanism for direct mitochondrial uptake and oxidation that involves a mLOC which probably works in parallel with malate-aspartate, glycerol-phosphate and other shuttles to balance cell redox and manage the lactate load from glycolysis under normal and stressful conditions (Brooks, 2020c)” [Brooks, G. A., et al.; 2021; 6].

Lactate is used permanently in other organs as well as in other muscle cells during exercise and in rest. Lactate is fundamental to

restore energy flux in the energetic system of locomotion especially with respect to glycolysis.

“However, because muscle lactate concentration exceeds that of pyruvate by one (10×) to two (200–400×) orders of magnitude in resting and exercising human muscles, respectively (Henderson et al. 2004), lactate oxidation is dominant in vivo” [Brooks, G. A., et al.; 2021; 5].

The energy system of locomotion with its internal processes is a representation of all expected stimuli. The different metabolic processes show the functional reaction of the system. The range of integration of different physiological and metabolic processes is the representation of the system’s adaptation towards future possible stimuli.

“Finally, because lactate exerts profound effects on fat and CHO metabolism, a poor lactate clearance capacity due to mitochondrial (mLOC) limitations greatly affect FATox and CHOox, which could result in metabolic dysregulation, and which, in turn, may give rise to IR, T2DM, and possibly other chronic diseases, including CMDs” [San-Millán, I.; Brooks, G. A.; 2017; 478].

With a strong inverse correlation between blood lactate and FATox as well as a correlation between FATox and carbohydrate oxidation, lactate shuttle plays a central role in assessing the integration of energy metabolisms in vivo [s. San-Millán, I.; Brooks, G. A.; 2017; 478].

“Recently, we have shown high inverse correlations ($r > 0.9$) between blood lactate levels and fatty acid oxidation rates. The inverse correlations hold on a wide range so human subjects ranging

from those with metabolic syndrome to elite athletes (64)⁴ [San-Millan, I., et al.; 2022; 9].

In this sense, lactate shuttle is an expression of adaption of the system and it's expected homeostasis. Translated form cybernetic theory into sport and training: lactate shuttle is an expression of training state and performance.

“Repeated lactate exposure from regular exercise results in adaptive processes such as mitochondrial biogenesis and other healthful circulatory and neurological characteristics such as improved physical work capacity, metabolic flexibility (Brooks, 2018), memory and cognition (Suzuki et al. 2011; El Hayek et al. 2019)” [Brooks, G. A., et al.; 2021; 15].

Measurement of lactate shuttle is only feasible with latest lab technology and not practicable in the field. But the insight that blood lactate is the sum of all appearance and usage with all active shuttles holds the opportunity of guessing the premises [s. Deuker, C.; 2017b].

“Recognizing that lactate, particularly rising blood lactate concentration, is a biomarker for an imbalance between lactate production and removal provides practitioners in diverse fields with important information on the physiological status of athletes and the ill and injured” [Brooks, G. A.; 2021; 1095].

With the lactate shuttle theory, it is possible to analyze the central parameter of an integrated metabolic system and draw conclusions for different, but integrated skills. This is interesting for tasks with

⁴ Ref. In citation: San-Millan I, Brooks GA. Assessment of metabolic flexibility by means of measuring blood lactate, fat, and carbohydrate oxidation responses to exercise in professional endurance athletes and less-fit individuals. *Sports Med.* (2018) 48:467–79. doi: 10.1007/s40279-017-0751-x

flexible loads like higher training impacts and the capabilities of an integrated metabolic system to cope with it through adaption and the setting of new probabilities to homeostasis.

“The results obtained here clearly show that PAs⁵ demonstrate superior capabilities to oxidize lactate, as well as CHO- and lipid-derived fuel energy sources, and also retain capacity for lipid oxidation at different exercise intensities where MAs⁶ and MtS⁷ patients are completely CHO-dependent, which is also expected as, especially for the MtS group, even the initial lower absolute intensities were metabolically tasking” [San-Millán, I.; Brooks, G. A.; 2017].

The idea of lactate guided threshold interval training (LGTIT) is not new [s. Casado, A., et al.; 2023; 1] and well established. ILSA wants to take the lactate shuttle as an internal index for the integration of the metabolic system instead of setting external distributions of training impacts. No doubt the idea of 80% in zone 2 is reasonable, but why not 79% or 81% and how to decide it? And where is your zone 2, especially when you think about sprint and maximal power workloads?

Measurements of blood lactate for guessing the lactate shuttle holds the opportunity of an internal factor for session planning. No doubt that for different training plans this information has not the same consequence, but it always shows the current integration of the system.

“No longer conceived of as a dead-end metabolite, a fatigue agent, or metabolic poison, in contemporary physiology, lactate is seen as

⁵ professional endurance athletes

⁶ moderately active individuals

⁷ metabolic syndrome

a major metabolic intermediate that has wide ranging impacts in energy substrate utilization, cell signaling, and adaptation; simply, lactate is at the fulcrum of metabolic integration" [Brooks, G. A., et al.; 2021; 2].

Lactate is the major myokine and most important factor of an integrated energy system. Changes in processes or subsystems are adaptations to environmental requirements. The flexibility of thresholds is an expression of integration of the whole system, which is represented by maintenance of energy flux and signaling of environmental stress to other system relations. Lactate shuttle and the related changes in blood lactate are a representation of these changes in an integrated energy system. An Integrated Assessment of Lactate Shuttle can serve as an internal variable towards system adaptations in supercompensation.

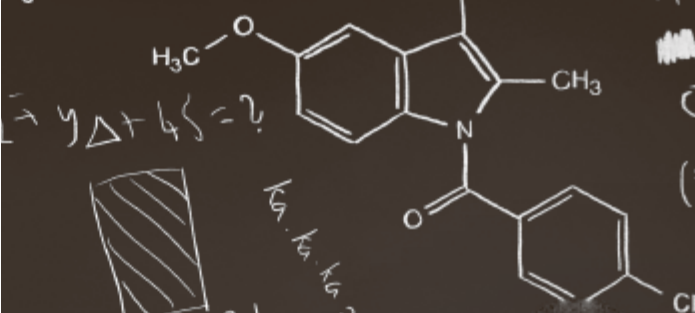
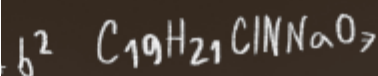
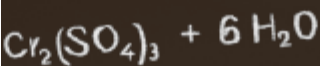
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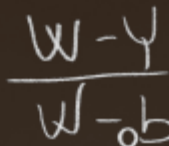


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$$k_a \cdot k_a \cdot k_a \approx k^3$$



$$A = 55\%$$

$$B = 18\%$$

$$C = 27\%$$



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○ - grey

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$$V = 216 \text{ cm}^3$$

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$$S = 6 \times 6^2$$

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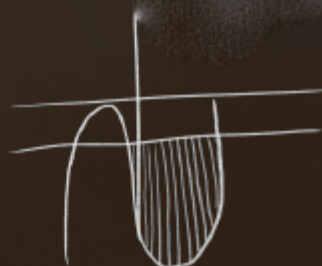
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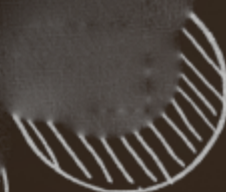
$$\sin(x)$$

$$\frac{1}{5} \pi (x^3)$$

$$\left(\int_{-\infty}^{\infty} x e^{-x^2} dx \right)^n$$



$$S = 9639.1$$



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